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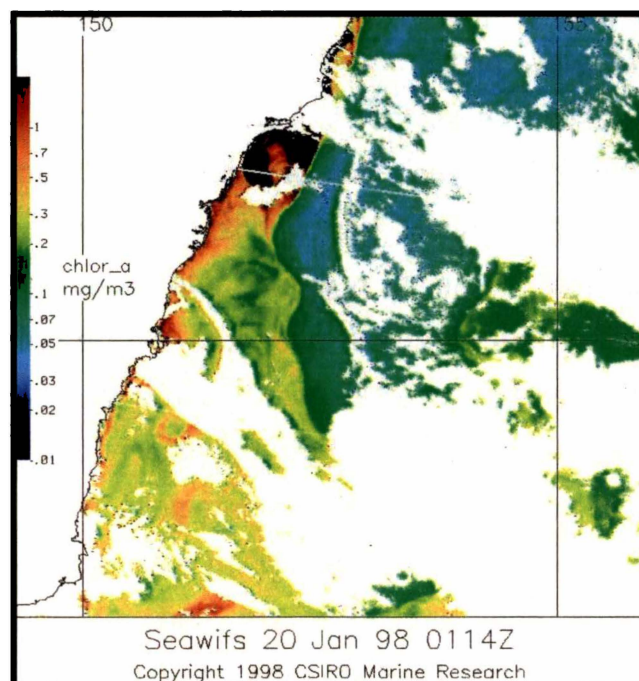
Partitioning the influence of anthropogenic and oceanic nutrient fluxes in the coastal ocean, and the question of cultural eutrophication

A thesis submitted in partial fulfillment of the requirements for the degree
of

Doctor of Philosophy in Earth Sciences

by

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extensive phytoplankton blooms in the study region as sensed by SeaWiFS satellite imagery

Abstract

A multi-disciplinary study was implemented in the mid 1990's in order to address concerns about apparent increases in the frequency and magnitude of marine phytoplankton blooms along the eastern Australian coast off New South Wales. This coastal region is frequently impacted by the western boundary flow of the East Australian Current (EAC), and anthropogenic discharges from major estuaries, and sewage outfalls within the Newcastle-Sydney-Wollongong conurbation. These coastal waters are typically nitrogen limited with respect to idealised Redfield ratios for optimal phytoplankton growth, indicating plankton sensitivity to nitrogen loading. Three deepwater outfalls servicing the city of Sydney represented the principal (~80%), continuous, anthropogenic source of nutrients to NSW coastal waters, predominantly in the form of ammonia nitrogen. The discharged effluent typically dilutes to 1:1000 to form plumes that remain trapped (~90%) by thermal stratification ($\geq 1^{\circ}\text{C}$), and are dispersed by the prevailing alongshore currents. Of the eleven coastal catchments in this study region, the large Hunter and Hawkesbury catchments account for ~80% of the total catchment area and account for the majority of catchment nutrient loads discharged into the ocean. These discharges only produced significant increases to coastal waters (mainly as silica) when major flooding breached strong salinity gradients in the lower estuary. Episodic slope water intrusions were identified as the principal source of nitrogen in the form of nitrate to coastal waters. These shelf encroachments occurred seasonally associated with strong thermal dynamics observed during spring and summer. An understanding of mechanisms of slope water intrusion emerged from the deployment extensive mooring arrays, modelling exercises and responsive sampling transects triggered by synoptic monitoring of telemetered moorings and satellite imagery. Slope water intrusions operated over (alongshore) length scales of hundreds of kilometres and over time scales of a few days to a few weeks. Intrusions were related to coherent alongshore wind induced upwellings and EAC shelf encroachments, and localised baroclinic instabilities on the shoreward edge of EAC formed by perturbations in shelf topography. Phytoplankton blooms were correlated to these slope

water intrusions irrespective of proximity to other major anthropogenic nutrient sources. However, the high frequency of occurrence of both the chain-forming diatom *Thalassiosira spp.* and the 'red tide' heterotrophic dinoflagellate *Noctiluca scintillans* during the study period was unprecedented in these waters. Long-term monitoring data indicated these anomalous conditions were associated with the strong El Niño episode of 1997/98, where warmer conditions prevailed. Corresponding studies along the New Zealand east-coast indicated a similarly unusual phytoplankton responses to El Niño episodes.

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Chapter One: Introduction and Thesis Approach

1-1 INTRODUCTION

In Australia, a recent environmental survey undertaken by the New South Wales Environment Protection Authority (NSW EPA), indicated ocean and beach pollution was regarded by the community as the most important environmental issue in NSW (EPA 1994). The significance of this statement was reinforced in this survey, by the fact that the environment was ranked, by the Government of the day, as the highest priority issue to be faced by NSW in the future (for 2004).

The national State of the Marine Environment Report identified that "Coastal eutrophication is a growing worldwide problem, and is one of the most serious, large-scale threats to Australia's near shore marine environment." (Zann 1995, Hallegraeff 1995). Long-term CSIRO monitoring (1960 to 1990) at Port Hacking (Sydney, see Figure 1-1) highlights this issue locally, with long-term increases in nutrient concentrations in Sydney offshore waters (Hahn et al 1977, Clayton and King 1990, Hallegraeff 1993b). This has been accompanied by an apparent increase in the frequency, extent and type of algal blooms in coastal waters (Grant and Kerr, 1970; Grant, 1971; Hallegraeff 1993b). Recently, an exceptional series of red tide blooms occurred in central NSW coastal waters during January and February of 1993 and was without precedent.

One of the most serious consequences of anthropogenic nutrient loading is that it tends to change normal nutrient balances ('cultural eutrophication') and thereby causes shifts in algal species composition. This was evidenced by the identity of the bloom organism *Noctiluca* - a eutrophication indicator - in the extensive red tides of early 1993 which stretched alongshore for ~300kms from Foster to Port Kembla (Hallegraeff 1993b).

Average concentrations of nutrients measured at sampling locations off Sydney (Coade 1995) have been found to be above values which elsewhere have been associated with algal problems (ANZECC, 1992, 2001). Insufficient information exists to determine, however, the relative significance of anthropogenic sources of nutrients, such as the offshore discharge of effluent, and/or natural phenomena (such as upwelling of nutrient rich ocean waters) to coastal eutrophication. Once this can be determined, the increased risk of algal blooms due to anthropogenic sources such as effluent discharged from ocean outfalls may be evaluated and used to prioritise and schedule reductions of discharges to oceans.

These issues prompted further investigations by the NSW EPA, resulting in the development of a major research program centered on the anthropogenically stressed coastal waters in the Sydney region (see Figures 1-1 and 1-2). The study region extends some 150km to the north (Port Stephens) and south (Jervis Bay) of Sydney to encompass both anthropogenic and oceanic nutrient sources, and to account for expected spatial lags in the phytoplankton response.

To ensure programs are founded on scientifically rigorous research, the NSW EPA encourages the project leaders to engage in a course of post-graduate research in tandem with the development of a NSW EPA program. This thesis represents such an opportunity. The following information in this chapter explores background studies in this field and identifies the shortfalls, outlines the specific thesis aims, and sketches how the development of the remaining chapters attempt to address them.

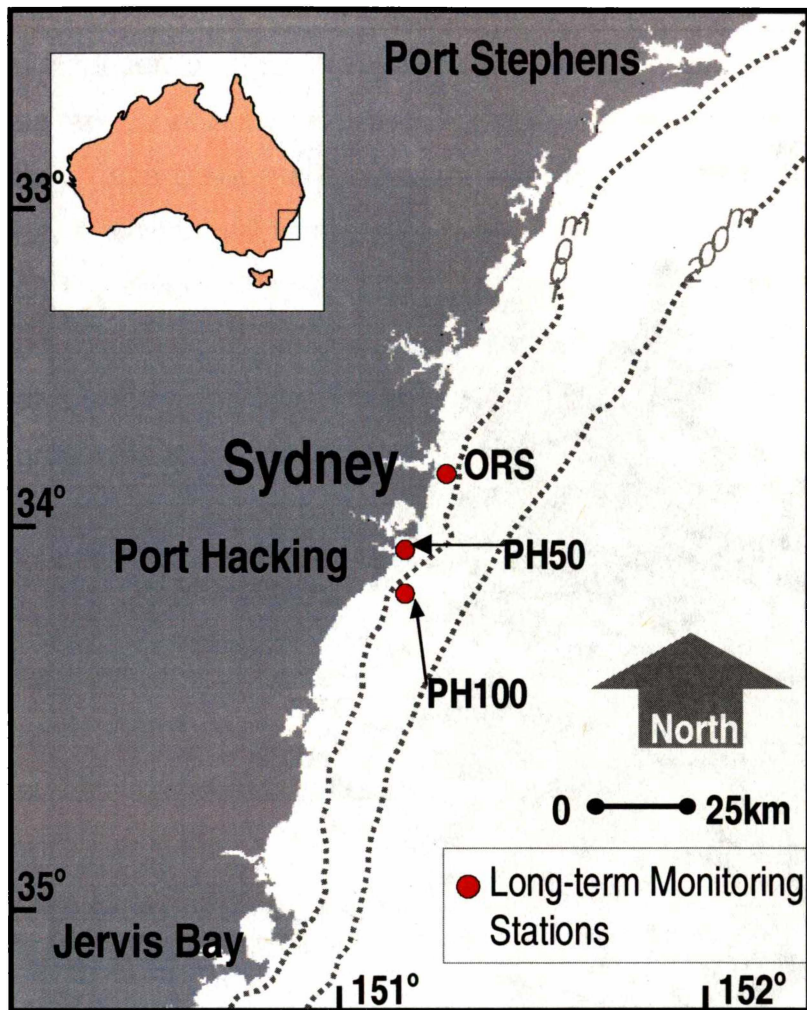


Figure 1-1: Locality diagram of the main study region off Australia's east coast, where anthropogenic discharges interplay with oceanic enrichments to formulate the local nutrient budget. Long-term sampling stations near Sydney provide the background information to the program.

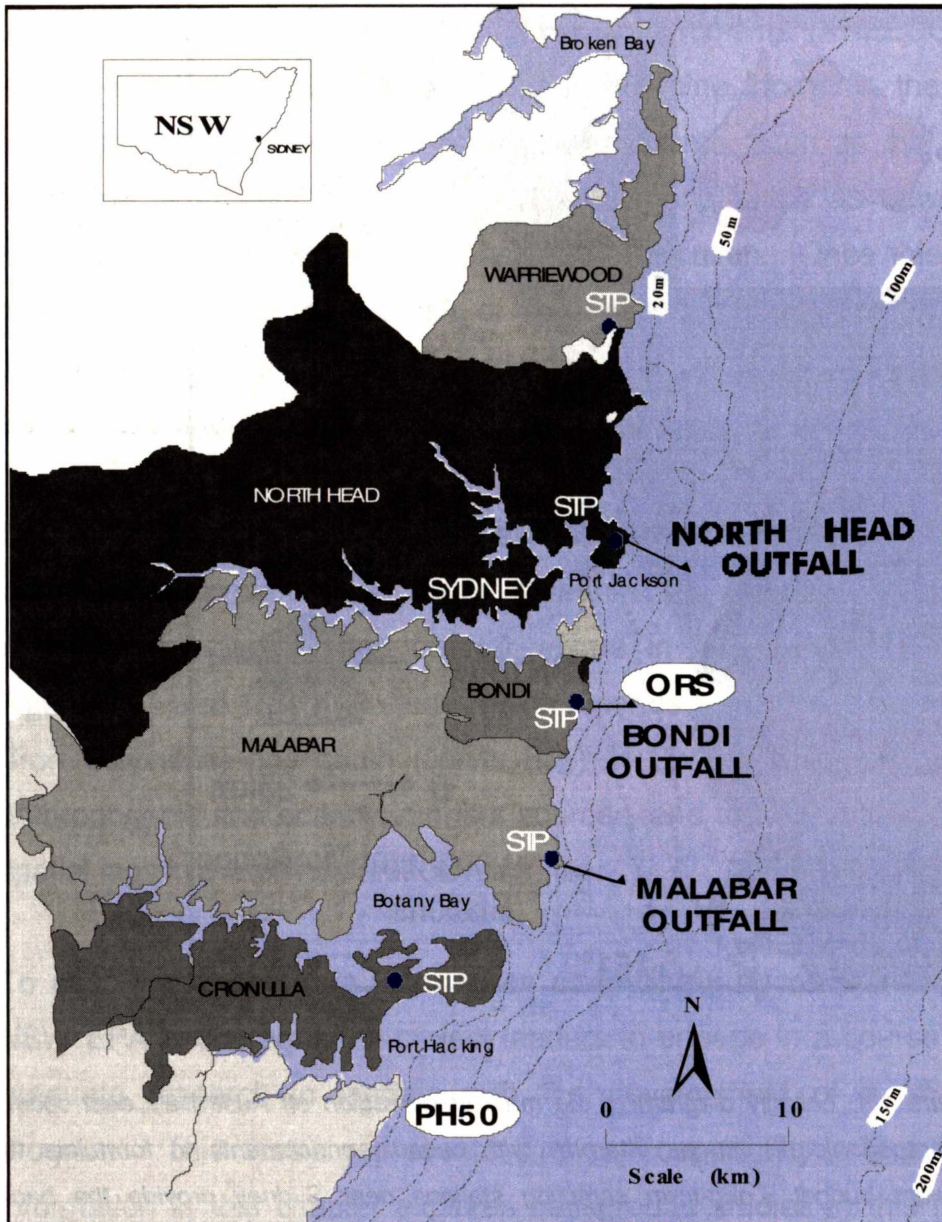


Figure 1-2: The Sydney region is a major source of anthropogenic nutrients discharging from three large deepwater sewage outfalls off North Head, Bondi and Malabar, and as estuarine discharges from Broken Bay, Port Jackson, Botany Bay and Port Hacking.

1-2 OVERVIEW OF STUDIES

Recent international studies indicate that the frequency, intensity and distribution of algal blooms are increasing. (Taylor, 1990). Blooms in the ocean are of such an extent that little can be done to manage them once they have developed. However if it can be shown that human activities have contributed to a bloom event, then these practices can be sourced and modified. Nutrient loading to coastal ocean waters however is often a complicated combination that is derived from a variety of sources (Gabric and Bell, 1993). Anthropogenic (land derived) inputs of run-off, groundwater, sewage and atmospheric pollutant fallout are fed into the coastal marine ecosystem. Superimposed on these nutrient discharges are “background” wind and current driven upwelling/uplifting of ocean nutrients, regeneration of nutrients in coastal sediments and natural fixation of atmospheric nitrogen that are sourced from the ambient ocean/atmosphere system. Rochford (1991) defines upwelling as a surface outpouring of these cool nutrient rich waters from the shelf slope, whereas uplifting describes the more frequent scenario of slope waters being brought inshore to the eutrophic zone.

Anthropogenic nutrients entered into the coastal environment undergo a variety of biological, chemical and physical processes that prolong their residence time and thereby limits their transfer to the open ocean (Anon, 1987). Nutrient cycling in coastal waters is simplified by Gabric and Bell (1993). Dissolved nutrients are taken up and incorporated into algal cells. With subsequent death, this particulate matter is deposited, and ensuing re-suspension and nutrient regeneration provides the water column with the dissolved faeces. The ultimate loss of nutrients from this system occurs through sediment burial, atmospheric discharge or the harvesting by higher trophic levels in the food chain. To avoid an overloading of this system, or eutrophication, it is vital that the introduced load of new nutrients doesn't exceed the capacity of the coastal system to process them.

One of the most serious consequences of anthropogenic nutrient loading is that it can change normal nutrient balances and thereby causes shifts in algal species composition ('cultural eutrophication').

Smayda and White (1990) and Hallegraeff (1993a) found that, other than nutrient enrichment from urban and industrial sources, increased bloom occurrences are also associated with the discharge of ballast water, shellfish transport and aquaculture activities. Taylor (1990) recognises that there is often a difficulty in delineating between natural oceanic fluctuations and progressive anthropogenic changes.

The question of climatic change and the algal response was treated by Hallegraeff (1993a). Inter-annual climatic fluctuations (eg. ENSO events) and dinoflagellate blooms in the Philippines were shown to be recurrent and Hallegraeff (1993a) raised concern that the present equatorial limit of harmful dinoflagellates could be extended further south (as indicated during the Pleistocene where there was a general ocean warming) with the greenhouse effect warming Coral Sea waters. Several internationally coordinated programs are presently in operation to investigate the links between harmful algal bloom events and climatic changes. Graneli et al (1990) and Chang (1995) show both an increasing distribution in the frequency of harmful blooms, and a continuous increase in the genera and species that are causing the blooms. Taylor (1990) suggests that blooms are often studied too late in their development, and that long-term field studies are necessary to provide clues for bloom indications such that a predictive capability can be achieved.

Hallegraeff and Jeffery (1993) provide a general outline of bloom development in coastal waters. A plankton bloom is preceded by an enrichment event, where nutrient levels are initially high and plankton levels low, and develops under favourable calm conditions (low turbulence in the water column). Newell (1966) suggests there is a 1-2 week lag between nitrate enrichment events and peak levels of plankton nitrogen. A "natural" oceanic enrichment is due to the vertical movement of nutrient

rich waters into the euphotic zone from the shelf slope. Following deep winter mixing and nutrient replenishment of the coastal zone, the combination of increased solar radiation and developed thermal stratification in the water column promotes a spring plankton bloom. Grazing and nutrient depletion ensures a subsequent bloom collapse and associated reduction in oxygen levels.

In assessing planktonic abundance in coastal waters several other “modifying” factors should be considered. Oviatt et al (1989) showed that when highly concentrated, self shading could limit plankton populations. Jenkinson and Wyatt (1995) indicate that the blooms themselves can change with their environment and also modify their surroundings e.g increased absorption of sunshine in the upper layer increases the surface temperature. Furthermore Oviatt et al (1989) indicated from field observations that the type of nutrients present in coastal waters could control the plankton populations. e.g. high nutrient water that suffers silicate depletion limits diatom growth but favours nanoplankton.

Studies in the North Sea and English Channel (CEC, 1991) displayed variations in the relative enrichment of nitrogen, phosphates and silica with respect to the flow regimes of the rivers discharging into the system. Long-term changes in coastal marine ecosystems have been identified by Gabric and Bell (1993) in the North and Baltic Seas. Here, coastal nutrient loadings have increased in the last 40 years from both point (e.g. sewage discharge) and non-point (e.g. agricultural run-off) sources, and subsequently coastal phytoplankton blooms have expanded both temporally and spatially.

Work overseas indicates that along with the long-term monitoring programs required to detect overall environmental changes, intensive short-scale investigations are necessary to understand dependencies and fluctuations in the coastal marine environment resulting from an enrichment event.

1-2-1 Local Issues - Australia and New Zealand

The Australian State of the Marine Environment Report identified that "coastal eutrophication is a growing worldwide problem, and is one of the most serious, large-scale threats to Australia's near shore marine environment." (Zann, 1995). Long-term CSIRO monitoring (1960 to 1990) at Port Hacking, Sydney, highlights this issue locally, with long-term increases in nutrient concentrations in Sydney offshore waters (Hahn et al 1977, Hallegraeff 1981, 1993b, Hallegraeff and Reid 1986). This has been accompanied by an apparent increase in the frequency, extent and type of algal blooms (eg Figure 1-3) in coastal waters (Hallegraeff 1995).

Figure 1-3: A highly visible algal bloom in the Illawarra region of the NSW coast, raises local concern for public bathing health.



Recently, an exceptional series of bloom events which occurred in central NSW coastal waters during January and February of 1993 was without precedent (Blackburn and Cresswell, 1993; Gibbs et al, 1997). These were paralleled on New Zealand's north-east coast where atypical species bloomed and were associated with widespread shellfish poisoning (Chang 1995). Table 1-1 indicates some of the recent blooming events for species which have occurred on Australia's east coast and in the north of New Zealand.

Table 1-1: Algal bloom species on Australia's eastern seaboard and New Zealand's North Island.

Algae	Australia	New Zealand	Effect
Raphidophyte flagellates <i>Heterosigma akashiwo</i> <i>Fibrocapsa japonica</i>	1980: Port Stephens 1991: Berowra Creek	1992: Coramandel (Aug-Dec) 1993: Hauraki Gulf (Aug-Dec) 1994: Hauraki Gulf (Aug-Dec)	Toxic to fish clogging of gills by mucus secretion and gill damage by hemolytic substances
Silicoflagellates <i>Dictyocha octonaria</i> (Aust) <i>Dictyocha speculum</i> (NZ)	1993: Newcastle (9-18 Feb)	1992: NE coast (Aug-Dec)	Silicious skeleton irritates gills, stimulating mucus secretion and lowering gill exchange potential
Coccolithophorids <i>Gephyrocapsa oceania</i>	1992: Jervis Bay (Dec'92-Jan)	1992: NE coast (Aug-Dec)	Both associated with an influx of cold nutrient rich water and high rainfall. Species likes micronutrients derived from land runoff
Dinoflagellates <i>Noctiluca scintillans</i>	1993: Foster to Pt. Kembla (Jan-Feb) 1995: Sydney to Jervis Bay (Jan-Feb)	 1995: Leigh-Hauraki Gulf (Dec'94- Feb) 1995: Coramandel (May)	Associated with calm conditions prevailing offshore winds (promoting upwelling) and high levels of ammonia (an indicator of bloom collapse)

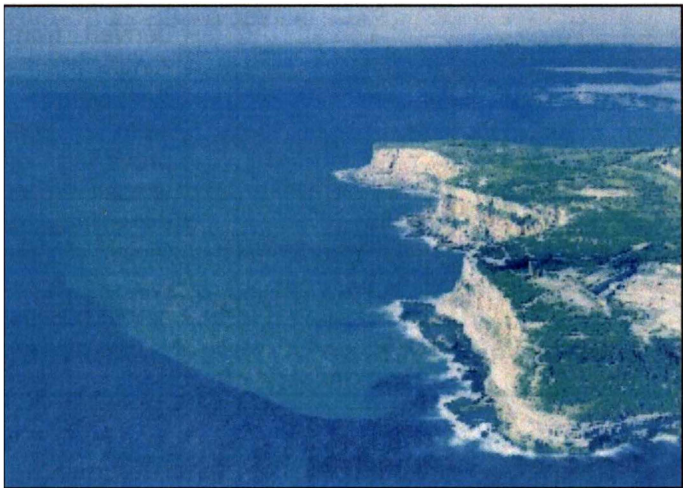
Hallegraeff (1993b) and Hodgekiss and Ho (1997) have suggested that nutrient sources could be characterised by the nutrient ratios of nitrogen, phosphate and silicates. These nutrients, in their biologically available forms, are the primary nutrients required for phytoplankton production, that is photosynthesis and cell division (ANZECC 1992). These nutrients, in low concentrations can limit phytoplankton growth, or conversely, in high concentrations can enhance algal growth. Australia and New Zealand Environment Conservation Committee (ANZECC) guidelines in Table 1-2,

provide a range of exceedence levels based upon prior known levels at which algal problems can occur.

Table 1-2: ANZECC guidelines for nutrient concentration exceedence levels

Constituent	Estuaries and Embayments	Coastal Waters
P0 ₄ -P	5-15 µg/L	1-10 µg/L
NO ₃ -N	10-100 µg/L	10-60 µg/L
NH ₄ -N	<5U µg/L	<5 µg/L
Chlorophyll-a	1-10 µg/L	<1 µg/L

Average concentrations of nutrients measured at sampling locations off Sydney (Coade 1995) have been found to be above values which elsewhere have been associated with algal problems (ANZECC, 1992). Similarly long-term measurements made at Leigh Marine Laboratories on New Zealand’s Northeast coast have indicated frequent high levels of total



nitrogen and ammonia that are well in exceedence of concentrations associated with blooms in the northern hemisphere (Ballantine pers comm).

Figure 1-4: Shoreline discharges of primary effluent were the major form of disposal until 1991 off the NSW coast. North Head outfall (off Sydney Heads) is shown in this example.

Australia’s population distribution has an urban and coastal focus with over 75% people living within 25 km of the coast, and a significant proportion lives beside an estuary (Fagan et al. 1992), placing considerable demands on the marine environment from industrial,

residential and recreational users. A high proportion of this coastal population lives within the region of Australia's largest city, Sydney. Here an example of significant anthropogenic nutrient loading to coastal waters occurs with a continuous discharge of sewage, industrial effluent and stormwater from 3.5 million people via 3 deep ocean outfalls, four coastal sewage outfalls, major estuaries and stormwater drains (see figures 1-4 and 1-5).

Direct monitoring of the impact of diffuse, subsurface effluent on marine waters was shown to be complex due to the high level of natural variability off Sydney (Lee and Pritchard 1995, Wilson et al, 1995). It was suggested that unrecorded rapid changes in oceanographic conditions may have contributed to the inability to detect significant differences in the abundance of larval fish, or in the community of larval fish, at sewage



(impacted) areas and control areas (Gray et al. 1992). Chlorophyll-*a* and nutrient concentrations observed during the EMP would have been confounded in a similar way.

Figure 1-5: Since 1991, deepwater outfalls discharge the majority of NSW's sewage load 3-4km offshore. Malabar outfall is shown in this Landsat satellite image as a surfaced plume.

Despite this background variability, water quality studies during the EMP indicated that from the time of operation of Sydney's offshore outfalls all

the offshore sites (from Long Reef to Port Hacking) generally increased in Chlorophyll-a regardless of longshore proximity to the outfalls. Pritchard et al (1995) found it was inconclusive as to whether nutrient loads from the outfalls were causing this increase as the study design did not allow an assessment of the relative nutrient contributions and their respective sources. The assessment concluded with the need for a better understanding of the contributions of nutrients to coastal waters, and that in subsequent studies greater analysis needs to be place on simultaneous observations of physical processes and nutrient and chlorophyll concentrations.

Insufficient information therefore exists to determine the relative significance of anthropogenic sources of nutrients, such as the offshore discharge of effluent, and/or natural phenomena (such as upwelling of nutrient rich ocean waters) to coastal eutrophication. Once this can be determined, the increased risk of algal blooms due to anthropogenic sources such as effluent discharged from ocean outfalls may be evaluated and used to prioritise and schedule reductions of discharges to oceans.

To date the majority of algal blooms in Australia has been considered naturally occurring (Jeffrey and Carpenter 1974, Hallegraeff, 1992). Rochford (1984) indicates from long-term data on the east coast, that blooms are frequently correlated with the intrusion of nutrient rich slope waters during spring and summer. However, the development of aquaculture in coastal regions since the 1980's has increased public sensitivity to the issue (EPA, 1994). Nutrient loading from increasing domestic and industrial discharges have been under scrutiny, and considered responsible for eutrophic conditions in coastal waters adjacent to major population centres. Sensationalist articles in the popular scientific press, such as Illert (1993) and Nolch (1993), have subsequently capitalised on these fears. Eutrophication is able to create shifts in bloom species by providing nutrient compositions that favour particular species. These shifts then have ramifications for the health and make-up of the marine ecosystem. An example is the toxic dinoflagellate *Gymnodium*

catenatum that was introduced via ship ballast water and has now become established within the Australian marine environment.

In the northern hemisphere the seasonal nutrient upwellings are dependant on deep winter mixing and internal nutrient regeneration, so that a bloom develops in response to enhanced solar radiation and the formation of stratification in spring (Hallegraeff and Jeffrey, 1993). Waters on the east coasts of Australia and New Zealand are more dependant on the activity of the prevailing offshore ocean currents to enrich them with deep ocean nutrients, and display their greatest phytoplankton abundance in early spring and late summer (Hallegraeff, 1992, Rhodes et al, 1993). These coastal waters also exhibit significant variance between years suggesting a long-term climatic control (Hsieh and Hamon, 1991).

1-2-2 Ocean dynamics

For many coastal ocean regions, significant upwelling of cooler nutrient-rich water occurs at the shelf break in response to persistent favourable wind forcing surface waters offshore. Akin to larger scale coastal upwelling, are more localised shelf-break upwellings induced by alongshore boundary currents that set up an unbalanced onshore-offshore pressure gradient. Embedded with these coastal currents are back-eddies that are formed from differential velocities of adjacent water masses or from interactions with shelf topography. The convergent eddies can locally enhance coastal upwelling by pumping waters below the nutricline to the euphotic zone. Changes in the orientation of the coastline and in local bathymetry can steer alongshore currents to locally enhance cross-shelf transports which can lead to instabilities and local upwelling similar to that described for the Agulhas Current by Gill and Schumann (1979). Anderson (1995) observed topographically driven instabilities on the inshore edge of the Gulf Stream that produced localised nutrient enrichments in coastal waters. Tee and Smith (1993) identified a three-dimensional topographically driven upwelling system off Cape Sable in south-western Nova Scotia where bottom topography variations induced an uplifting of slope-waters which were advected alongshore by a prevailing coastal

current. This system allowed the upwelled nutrients to be supplied to coastal waters downstream of the upwelling zone and enhancing phytoplankton populations (Ryan et al, 1999).

The three scales of coastal upwelling identified here, operate upon the same basic principles. Briefly, the locally lowered sea level has a reduced water column mass, thereby decreasing the fluid pressure below the surface. Mechanics require fluids to flow along isopycnals from higher to lower pressures, so sub-surface waters flow inshore towards the regions of locally lowered pressure. The advected nutrient rich subsurface waters brought to the euphotic zone are monopolised by the food chain. Their significance is such that although coastal upwelling regions comprise ~0.1% of the ocean surface, they produce approximately half of the exploitable fish biomass (Ryther, 1969).

On western oceanic boundaries the mean wind field is not conducive to the persistent upwelling as seen off Peru, Oregon and NW Africa. However, transient upwelling favourable winds on the western boundaries can lead to episodic coastal upwellings when durations of the favourable weather patterns persist for a day or more, as observed on the south-eastern US continental shelf by McClean-Padman and Padman (1991). Similar to this region, they noted that the shelf off eastern Australia is only affected by upwelling favourable winds (from the NE sector) when high pressure systems are situated offshore. These events usually occur during summer months and persist for several days generating short-term coastal upwellings.

The predominant SE trades in the South Pacific Ocean drive an anti-clockwise subtropical gyre that intensifies on the western boundaries. The two main western boundary currents formed are respectively the East Australian Current (EAC) and the East Auckland Current (EAC-NZ). This system has its strongest flows in spring and summer and weakest flows in winter, and is well documented in Cresswell et al (1983), Godfrey et al

(1980), Tranter et al (1986), Stanton (1979), Denham et al (1984), and Stanton et al (1996).

These studies depict a southward flow stream along the east Australian coast from ~18°S to ~32°S, that splits into a meander (Tasman Front) extending to New Zealand, and a turbulent eddy field that entrains this warm Coral Sea water into the cooler Tasman (Figure 1-6).

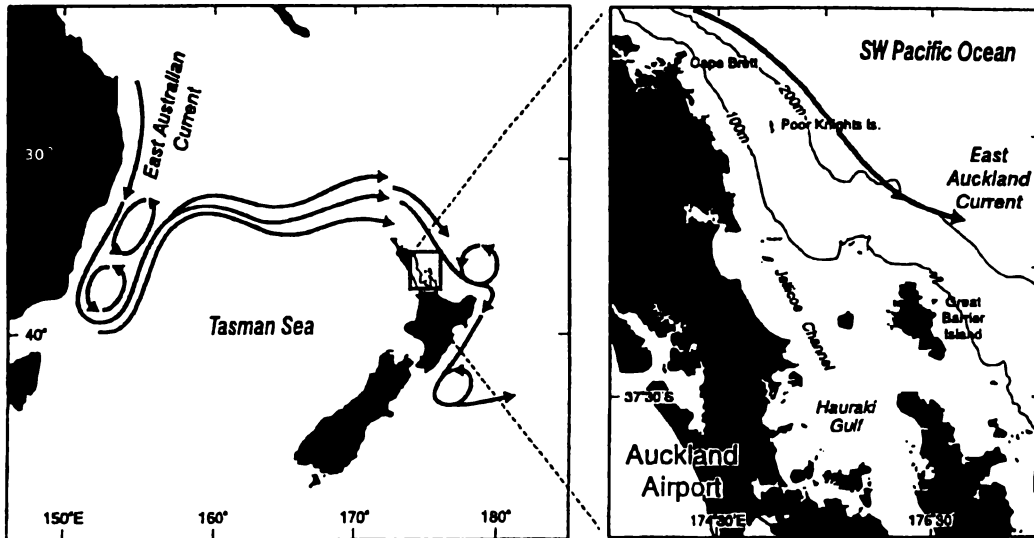


Figure 1-6 East Australian and East Auckland currents forming the western boundary flow of the South Pacific Gyre.

The location of the Tasman Front appears to be seasonal and varies inter-annually (Stanton, 1979, 1981). Its eastward entrainment (at around 0.65ms^{-1}) of subtropical Coral sea waters eventually reaches New Zealand after some 6-18 months transport forming the EAC-NZ (Sharpley, 1996). This flow streams southward along New Zealand's northeast coast, becomes somewhat divergent in the Hauraki Gulf, before intensifying as the East Cape current and then heads east into the Pacific as a return flow.

The Tasman Front essentially links the EAC and the EAC-NZ as part of the subtropical gyre that exists in the South Pacific. Dynamics of this gyre have been suggested to be linked to long-term climatic oscillations such as the El Niño Southern Oscillation (ENSO) and anti-ENSO conditions.

Sprintall et al (1995) indicated there was a decrease in the flux of water through the Tasman Sea during the strong ENSO of 1992, seen locally as anomalously cooler coastal water temperatures (Ballantine, 1995). Lee and Pritchard (1996) indicated that anomalously low thermal stratification was associated with a reduced frequency of EAC shelf intrusions during the same period on the NSW shelf. Sprintall et al (1995) suggested the Tasman Sea experienced a eastward divergence of warm surface water prior to the anomalously cool conditions indicating large scale upwelling was in operation on the western boundaries of this “weakened” subtropical gyre. Rhodes et al (1993) and Taylor et al (1985) both cite these anomalously cool ocean conditions as correlating to strong ENSO events of 1992 and 1983, and responsible for two of the most extensive and damaging algal blooms on the northeast coast in recent recorded history.

Shorter intra-seasonal time-scale upwelling/lifting of nutrient rich slope water onto the East Australian shelf often occurs along the edge of the Great Barrier Reef south to Port Stephens when the EAC meanders offshore. The EAC eddy field can similarly drive slope waters onshore when encroaching on the shelf, or act as a nutrient source when there is deep convective overturning within the eddy. Typically upwelled waters have temperatures $<14^{\circ}\text{C}$, pH <8.15 , phosphate $>21\text{ }\mu\text{g/L}$ and nitrate $>70\text{ }\mu\text{g/L}$ (Cresswell, 1994). An example of these dynamics was observed by Hallegraeff and Jeffrey (1993) where widespread diatom blooms extending from the EAC-A separation point (at 32°S) to Tasmania were associated with slope water enrichments from the EAC-A eddy field.

Recent studies in coastal waters of Northeast New Zealand (Sharples, 1996), has indicated similar on shelf intrusions of warm saline nutrient poor water ($>18^{\circ}\text{C}$, $>35.5\text{psu}$) from the EAC-NZ, that was overlying cool nutrient rich waters inshore ($<14^{\circ}\text{C}$, $<35.3\text{psu}$). Enhanced fluorescent levels detected on the thermocline supports the suggestion that the EAC-NZ influence on the shelf had caused an uplifting of slope waters. Further down the EAC-NZ flow stream at East Cape, Bradford et al (1982) related prevailing upwelling to moderate phytoplankton concentrations confined to

the shelf and near-slope waters peaking around 50 m depth. The upwelling of nutrient rich slope water (nitrite-nitrate nitrogen $>40 \text{ mg/m}^3$) was due to the EAC-NZ flow stream running over the Ranfurly Banks and deep mixing set-up in the lee of East Cape. Bradford et al (1982) compared these eddy enrichments to similar conditions experienced with the EAC eddy field (Tranter et al, 1986).

Although there appear to be similar conditions experienced on the respective continental shelves with the EAC and EAC-NZ systems, there clearly too are differences. Comparing results from Stanton et al (1996) and Cresswell et al (1983) flow strengths of the EAC are 1-2 m/s, whereas the EAC-NZ is in the range $0.2\text{-}0.6 \text{ ms}^{-1}$. Therefore the greater dynamics on the Australian coast would promote more intensive upwelling scenarios than experienced in New Zealand waters.

The eastern Australian seaboard provides a narrow and fairly straight shelf of some 1500 km down which the EAC can flow. There are minor embayments and protrusions that introduce turbulence to the flow, but in-general fluctuations of the EAC and it's eddy field, is driven by the climatic dynamics of the South Pacific Gyre (Lee and Prichard, 1995). In contrast, the much shorter eastern shelf of New Zealand's North Island is convoluted with large topographic protrusions and embayments. EAC-NZ flow on this shelf is further complicated by turbulent flows that are set-up by the numerous islands. This increased ocean-shelf turbulence on the New Zealand shelf would be expected to promote a greater frequency of slope water upwelling/upliftings. Oldman et al (1996) have identified intense upwelling along the Northland coast near the Rimariki transect and off the Great Barrier island, under favourable conditions. Upwelling on the narrow shelf to the north near Cape Brett, and topographically-induced turbulence in the lee of the Cape, could provide a scenario where uplifted slope-waters are then carried into the Hauraki Gulf with the southward current enhancing the local plankton populations. Figure 1-7, schematises the upwelling/uplifting processes relative to anthropogenic loadings in the coastal zone.

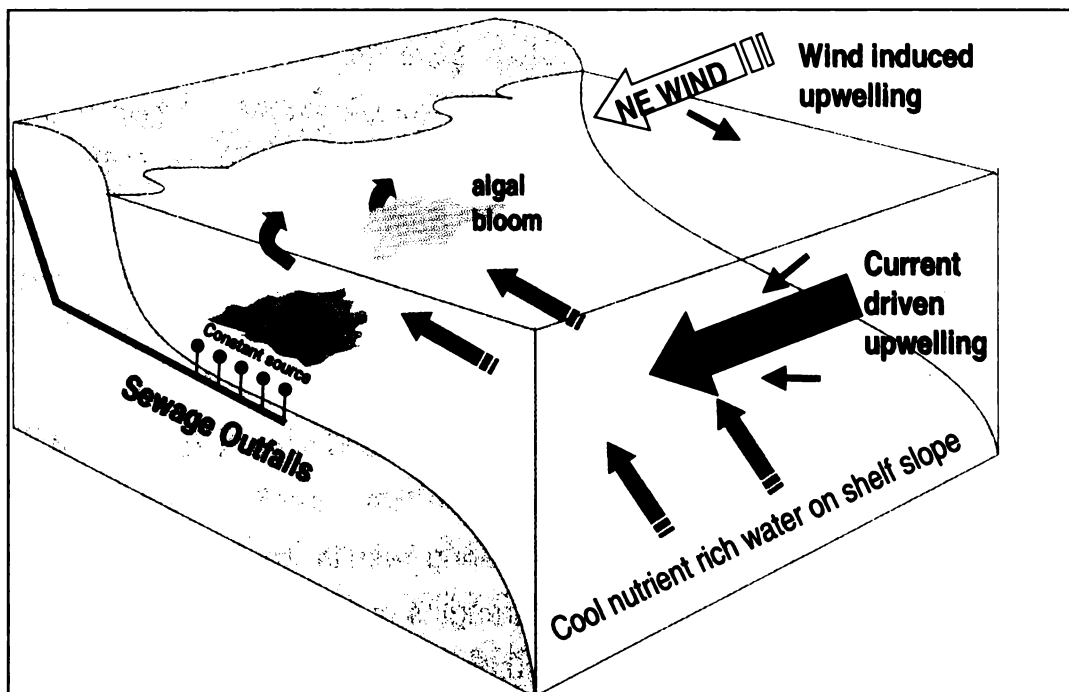


Figure 1-7: Schematic of major nutrient sources influencing coastal waters in the study region. Coastal upwelling forced by western boundary currents and regional winds drives nutrient rich waters from the shelf slope inshore, anthropogenic discharges from deepwater sewage outfalls and estuaries enriches coastal waters. Plankton located in the euphotic zone (typically on or above the thermocline) respond to these sources.

1-2-3 Knowledge Shortfalls

From the previous work outlined a number of questions have either arisen or remained.

- what are background nutrient concentrations and ratios in NSW coastal waters and how does variability relate to oceanographic processes?
- what are the relative nutrient loadings to NSW coastal waters?
- what are the nutrient concentrations and ratios from anthropogenic sources, and what is the significance of their impact on ambient nutrient concentrations in NSW coastal waters?
- to what extent do the dynamics of the East Australian Current affect shelf waters, with respect to more localised forcing (e.g. wind induced upwelling)?
- what are the nutrient, oceanographic and algal processes involved prior to, during and following a bloom event?
- how does the response of algae to enrichment (oceanic or anthropogenic) differ for different species and what is the relationship between algal response and nutrient distribution?

- can we characterise typical algal successions that takes place during a bloom event and can we relate them to nutrient distributions?
- what relationship exists between the duration of the upwelling and the duration of the bloom?

1-3 OBJECTIVES

This study aims to determine the relationship between physical oceanographic conditions, chemical concentrations and the occurrence of algal blooms on the east coast of New South Wales. This coastal region is affected by the dynamics of the East Australian Current, and anthropogenic nutrient inputs from major estuaries and sewage discharges within the Newcastle-Sydney-Wollongong conurbation. The overall goals of the project are to;

1. To understand the relative roles of oceanic and anthropogenic nutrients, in the development of plankton blooms within a dynamic coastal environment,
2. To address the issue of cultural eutrophication, ie. is the nutrient composition changing in coastal seas, and how is this affecting the planktonic types, their distribution and abundance?
3. Consider and compare findings with a relatively anthropogenically unimpacted coastal region which is influenced by strong oceanic nutrient fluxes.
4. Indicate how representative the study was in the context of long-term climate variation.

by:

- Characterising oceanic and anthropogenic nutrient fluxes from data recorded during 3 years of intensive field programs within a 300km alongshore section of the NSW continental shelf between Port Stephens and Jervis Bay.
- Defining the major anthropogenic sources in the study region from catchment monitoring records, treatment plant flow data, and specific flood discharge experiments.
- Utilising temperature-nutrient relations for application of temperature criteria to assess temporal and spatial characteristics of oceanic slope-water intrusions.
- Comparing dynamics and nutrient regimes obtained through a companion study program off the east coast of New Zealand's North Island.
- Investigating how physical oceanographic conditions and anthropogenic sources relate to the type, size and abundance of phytoplankton.
- Referencing long-term records to address effects of climatic variance on the study outcomes.

1-3-1 Assessment approach

This thesis is based on an extensive three-year investigative program initiated and implemented by the author as an employee of the New South Wales Environment Protection Authority (NSW EPA), Australia. This work is supplemented by studies conducted within the Earth Sciences Department, University of Waikato and the National Institute of Water and Atmospheric research (NIWA), New Zealand.

In Australia, the Ocean Nutrient and Phytoplankton Project (ONPP) was a large collaborative study coordinated by the Marine Waters Unit of the NSW EPA, and the Biological Science Department of the University of New South Wales. The investigations occurred between 1995 and 1998 and involved intensive field campaigns to capture physical, chemical and biological conditions in relation to the various nutrient inputs introduced to coastal waters on the New South Wales continental shelf. With the emphasis of the program centred on the Newcastle-Sydney-Wollongong conurbation, the program takes advantage of long-term monitoring data collected back to 1942 off Sydney. Port Stephens and Jervis Bay were encompassed into the study region as they have a history of slope water upwelling and bloom events but they do not appear to be associated with local anthropogenic nutrient sources.

The information obtained from New Zealand, has associations with NIWA's Nearshore Offshore Exchange program (NOEX) that was conducted during 1993 to 1996 off the east coast of the North Island to examine the exchange of sediments and nutrients along and across the continental shelf. The north east coast of New Zealand was selected for the PhD study due to its proximity to the free flowing Auckland current and a relatively similar shelf profile to the NSW coast, in an attempt to compare with the East Australian Current shelf impacts on the NSW coast. The section of coast north of the Poor Knights Island group (see Figure 1-6) was selected as it was clear (to the north) of islands, had a relatively straight coastline paralleled by the bathymetry and forms the upstream boundary of the Hauraki Gulf where phytoplankton blooms have been of

interest. This region was therefore expected to be influenced by a relatively uninterrupted stream of the East Auckland Current.

In addressing the aims and objectives, the thesis combines information from the aforementioned programs in order to relate nutrient fluxes from anthropogenic discharges and ocean forcing. Investigations will be collating information on anthropogenic nutrient sources, quantifying the physico-chemical characteristics of oceanic waters influencing the shelf, and defining the physical characteristics of the circulation, including the upwelling/uplifting and downwelling events that cause cross-shelf nutrient exchange. The project will then interpret these results in relation to algal events over several years using measurements of plankton type, distribution and abundance.

This multi-disciplinary approach is well suited to address the most important questions with respect to cultural eutrophication, ie. is the nutrient composition changing in coastal seas, and how is this affecting the planktonic types, their distribution and abundance? Although it is difficult to record long-term changes within the confines of the 3-year program, the combination of both pristine and heavily urbanised coastlines within the study region could spatially define these changes.

1-4 THESIS STRUCTURE

The findings from this thesis are presented as a combination of seven peer-reviewed papers assembled into five thematic results chapters (3-7). These chapter themes *Anthropogenic Sources*, *Oceanic Processes*, *Oceanic Nutrients*, *Phytoplankton Responses* and *Long Term Patterns*, are maintained in the supporting chapters for easy reference. Five of these papers have undergone peer review and have been published during the course of the thesis program. The remaining papers have undergone external reviews and are currently submitted for publication. Where possible, the chief PhD supervisor, Dr. Kerry Black, and the NSW EPA Marine Waters Manager, Mr. Tim Pritchard, have been included in the author listing to acknowledge the collaboration between the University of Waikato and the NSW EPA. For each of these chapters an introduction threads together the main arguments that the papers explore, and a short discussion at the chapter's conclusion highlights the findings. For all the published papers the specific journal formats (such as referencing and scientific units) have been retained to faithfully present the papers as the published text.

1-4-1 Main Themes

The chapter themes for this thesis have been designed to build a story around the major influences and the resulting responses that phytoplankton populations experience within the selected coastal study region. **Chapter 1** introduces the issues and develops the approach that the thesis takes in an attempt to resolve them. **Chapter 2** details the data information that was measured or obtained for the results presented within the succeeding chapters. Anthropogenic nutrient inputs to the coastal region are explored in **Chapter 3**, focussing on sewage outfall and coastal catchment discharges into the adjacent coastal waters. Oceanic conditions affecting coastal waters are investigated in **Chapter 4**, where the influences of western boundary current dynamics and wind forcing are compared. Scenarios of these mechanisms are investigated further in **Chapter 5** as a mediator of oceanic nutrient enrichments to shelf waters. **Chapter 6** builds upon the information in the preceding chapters to

investigate how phytoplankton respond to the relative nutrient loadings. In the light of the information obtained during the field program, long-term variability of physico-chemical factors are assessed in **Chapter 7** to provide these studies with a greater temporal context. The project findings are re-capped and compared in an in-depth discussion that expands on the original project objectives in **Chapter 8.**, drawing towards conclusions in **Chapter 9.** The following section introduces the thesis development by chapters detailing the main themes pursued and identifying the information obtained and the noting the personnel who were involved.

1-4-2 Data Information

To assist in understanding the development of the thesis study program, the data information collected for each of the four main result chapters (3-6) are presented separately in this chapter. The chapter details key data sources that were utilised throughout the thesis and initially reviewed for knowledge shortfalls, and outlines the five major field campaigns that were undertaken to resolve these gaps. These field campaigns undertaken predominantly in Australia included;

1. wet weather sampling of major estuarine discharges,
2. routine cross-shelf sampling transects to spatially and seasonally define shelf conditions during the program (also in New Zealand),
3. the deployment of an alongshore thermistor array to spatially and temporally define upwelling in the study region,
4. repetitive transects during upwellings to capture phytoplankton bloom development,
5. and a 12-month weekly sampling campaign to revisit studies undertaken 20 years previous.

Key data sources referenced for anthropogenic nutrient sources (Chapter 3) included sewage treatment plant flow data, NSW EPA sewage plume modelling, meteorological records, and flow gauging network of coastal catchments, Oceanic data sources in Chapters 4-6 included long-term

monitoring stations off Port Hacking and Bondi(Sydney), hydrographic cruise data along Australia's east coast, regional data assimilation model results, satellite imagery of calibrated sea surface temperature and chlorophyll-a reflectance, and long-term records of the southern oscillation index. The information in Chapter 2 has also been presented in a series of four data reports written during the study program (as summarised in Appendix 1).

1-4-3 Anthropogenic sources

This chapter draws together two papers that were written during the study, to explore the various anthropogenic nutrient sources within the study region. The chapter addresses the first and second thesis objects by attempting to quantify and characterise the anthropogenic nutrients entering the adjacent coastal waters.

In the first paper presented in this chapter, anthropogenic loads are reviewed prior to exploring the principle anthropogenic source in the region. The paper, entitled "How do ocean outfalls effect nutrient phytoplankton relationships in coastal waters of New South Wales, Australia?" was presented by Mr. Tim Pritchard at the International Coastal Symposium in Rotorua, April 2001 and published in a special issue of the Journal of Coastal Research, 34 (2001). The paper investigates the patterns of nutrient enrichment due to the three major ocean outfalls off Sydney using a 6-year record of effluent plume model simulations (based on assessments by Lee and Hall, 1994), effluent quality data and long-term records of ambient nutrient concentrations. To provide a comparative context of this anthropogenic load, typical estuarine discharge loads from the eleven coastal catchments are referenced and discussed. As a co-author to this paper, and through extensive experience in sewage plume observations and modelling (Lee and Hall 1994, Lee and Pritchard 1995, Lee and Pritchard 1996), the thesis author was closely allied to the paper development and the ideas it discusses.

The second paper investigates anthropogenic loading from coastal catchments within the Port Stephens to Jervis Bay study region. The paper, entitled "Extreme discharges into the coastal ocean: A case study of August 1998 flooding on the Hawkesbury and Hunter Rivers", was presented at the Pacific Coasts and Ports Conference in Perth 1999 and the full paper was peer reviewed for publication in the proceedings. Background information indicates that nutrient discharges from well-developed estuarine systems in the study region occur during flooding when the fresh discharge can override a strong horizontal salinity gradient. Focus on limited information that captured flood events developed the need for this sampling study. This paper presents a case study of wet weather events in July/August 1998 that caused major flooding of the Hunter and Hawkesbury rivers. These two systems make up some 80% of the total catchment area of the eleven coastal catchments that reside in the study region. As principle author of this work, I was instrumental in the design, operation and analysis of this campaign, and provided strategic guidelines for the initial literature review (SKM, 1998). This information was obtained by contract, as data records (gauging, monitoring programs, field experiments, etc) resided within a variety of agencies and were unavailable directly to the NSW EPA. As with all field components in the ONPP, the water sample analysis was performed by the NSW EPA laboratories. The paper acknowledgements detail the personnel who assisted with the field exercises. Supporting satellite imagery was provided in-kind as the ONPP reciprocated with ground-truthing information. The results from this chapter are drawn together in the Overview chapter (7) papers, and explored further in the final discussion chapter (8).

1-4-4 Oceanic Processes

This chapter investigates a ~300km alongshore stretch of the study region off Australia east-coast using a recognised temperature signature to identify nutrient-rich intrusions from the shelf slope. The results are presented as a paper, entitled "Scaling coastal upwelling features in the region of the East Australian current eddy field". This paper was presented at the Australian Marine Science Association conference in Sydney, 2000,

and has recently been submitted to Continental Shelf Research for publication. This work obtained information from a 12-month deployment of thermistor and current moorings located in coastal waters at 50 and 100m depths. Temperature structure is used to investigate the frequency and extent of intrusions of cool, nutrient rich slope-waters, in both a spatial and temporal context. Results from five years of data assimilation modelling are calibrated and interpreted to enhance this understanding. The design concept of the mooring array was developed, by the thesis author during the ONPP, as a novel means of quantifying slope-water intrusions in the study region, and to provide compatible quality long-term results to test the alongshore coherence of the historical records off Sydney. The co-author Clive Holden assisted with the regular maintenance and logistical support for over twenty moorings that were operative during the 12-month deployment period. Stephanie Wallace also appears as a co-author to acknowledge her assistance with Matlab routines that drove the time series analysis of the thermistor data.

The NSW EPA contracted the CSIRO Marine laboratories in Hobart, Tasmania to simulate temperature fields in the study region based on their empirical model developed for the Climatology of Australian Regional Seas (CARS) to address monitoring in the Australian Ocean's Economic Exclusion Zone (Ridgeway, 1996, Ridgeway et al, 1997). Model details are provided in the paper and in Chapter 2. Paper acknowledgements also detail the support from the field crew, and CSIRO personnel who provided the long-term cruise and station data used in this paper.

1-4-5 Oceanic Nutrients

The second paper addressing oceanic sources details the nutrient dynamics associated with slope-water intrusions, and combines this multi-disciplinary information to address the third thesis objective. Physico-chemical data, water quality and plankton samples were collected as routine and responsive shore normal transects taken off the NSW coast during the 1990's. The work presented here characterises temperature-nutrient associations with slope-water intrusions, and comparisons are

made to address event patterns and the subsequent algal blooms observed. From this work, the paper, entitled "The influence of western boundary currents off the east coast of Australia on phytoplankton dynamics in the coastal zone", was presented at the Plankton Symposium in Portugal, September 2001, and is currently scheduled as a paper in the Elsevier Science journal publication, *Acta Oecologica*. The routine field sampling was designed, coordinated and implemented by the thesis author, however a field exercise of this scale required a coordinated support team. Paper acknowledgements list the personnel who assisted in the field with sampling. The co-author, Penny Ajani, provided expertise regarding algal species identification and numeration. The groundwork from this routine sampling segues to the understanding of phytoplankton responses developed in the following chapter.

1-4-6 Phytoplankton Responses

This chapter addresses the first two thesis objectives by exploring phytoplankton responses to conditions in coastal waters. The critical factors that control (limit) phytoplankton populations are addressed through historic review, and an understanding of their interactions with nutrients and dynamic processes developed during these studies.

The first paper details a case study of a major upwelling event which was accompanied by numerous reports of algal blooms. The work neatly combines physico-chemical observations and predictions with an enhanced phytoplankton reality. The paper, entitled "Anomalous upwelling along Australia's east coast", was presented at the International Coastal Symposium in Rotorua (NZ), April 2000, and recently published in a special issue of the *Journal of Coastal Research*, 34 (2001). It and focuses on results obtained by repetitive cross-shelf transects off Port Hacking (Sydney) during an intrusion event in January 1998. Synoptic measurements of ocean temperature triggered this responsive sampling program, which had been on call since the beginning of the 1997/98 algal bloom season. The sampling was supported by the alongshore array of temperature and current moorings concurrently in operation, and ground-

truthed satellite imagery of chlorophyll-a reflectance. This work was driven and assessed primarily by the thesis author, with co-authors Ajani and Wallace respectively assisting in their roles from the previous chapter.

The second paper provides an overview of responses through a 12-month sampling program that replicated studies done 20 years earlier in an attempt to resolve any gross changes. The paper entitled "Phytoplankton populations at CSIRO's long-term coastal station off Sydney", was also presented at the International Coastal Symposium April 2000 and published in issue 34 of the Journal of Coastal Research (2001). It explores the phytoplankton assemblages and their physico-chemical environment during 1997-98 at a long-term coastal monitoring station off Sydney and compares them to those seen previously seen at this location. Quantitative plankton sampling, along with routine water quality and instrumental station profiles, was performed weekly throughout the 12 month study. Penny Ajani was the principle author for this paper as the majority of the work in this paper was involved in intensive phytoplankton processing (counts and identification). The oceanographic conditions that influenced phytoplankton populations for both 12-month studies were interpreted by the thesis author. Both authors were routinely deployed on the weekly outings and involved in the logistical coordination. The NSW EPA's biometrician, Martin Krogh, is also authored on this paper for his role in operating the Principle Component Analysis of the plankton biomass. The paper has been included in this chapter as it provides key seasonal information and background data for the physico-chemical component s to reference.

These two papers were both presented at the International Coastal Symposium in Rotorua, April 2000, and have recently been published in issue 34 of the Journal of Coastal Research (November 2001).

1-4-7 Long-Term Patterns

The outcomes of short-term studies are often interpreted as general assessments but may be heavily biased by natural long-term variability.

This paper presented in this chapter utilises long-term records off Sydney (~58 years) to explore the extent to which differences in nutrient concentrations and phytoplankton patterns may be due to large scale climate variability. The paper, entitled "Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia", was presented at the International Coastal Symposium in Rotorua, April 2000, and published in a special issue of the Journal of Coastal Research, 34 (2001). The work initially questions the long-term record data quality to determine its temporal and spatial limits, prior to assessing the climatic variance of physico-chemical parameters for seasonal, inter-annual and long-term scales. The influence of El Niño episodes resolved from the long-term records is used to indicate its relative influence to the more commonly defined seasonal signal. Results from the ONPP are tested against the resolved El Niño signal. The thesis author has a prior publication (Lee and Pritchard, 1996), which provided an initial foundation to the tangent developed in this chapter. Penny Ajani has been included as an author on this paper for her analysis of the phytoplankton data from the 12-month study in Chapter 5. The outcomes of this chapter focus on the fourth thesis objective, and provide a degree of confidence that can be applied to the program's findings.

1-4-8 Discussion

This chapter discusses and develops findings from the study with respect to the original four thesis objectives. regarding effects that anthropogenic discharges (predominantly shown as sewage outfalls) are likely to have on phytoplankton populations. Evidence is also discussed regarding other influences that may be responsible for any changes in phytoplankton populations, including a range of sources that may have been neglected from the study program. By such methods the question of cultural eutrophication is developed against clearly demonstrated outcomes of the program to indicate how this globally perceived problem is manifested on a local level.

1-4-9 Conclusions

This chapter finalises the thesis objectives by outlining the main conclusions from the studies undertaken during the program. It also details unresolved issues that has arisen from these studies and provides an indication for future research and collaboration with regulatory monitoring agencies.

Chapter 2: Data information

2-1 ANTHROPOGENIC SOURCES

The significant anthropogenic sources for the coastal region between Port Stephens and Jervis Bay on the NSW coast are discharges from coastal catchments and sewage outfalls. The map in Figure 2-1 locates the catchments and major coastal sewage discharges in the study region.

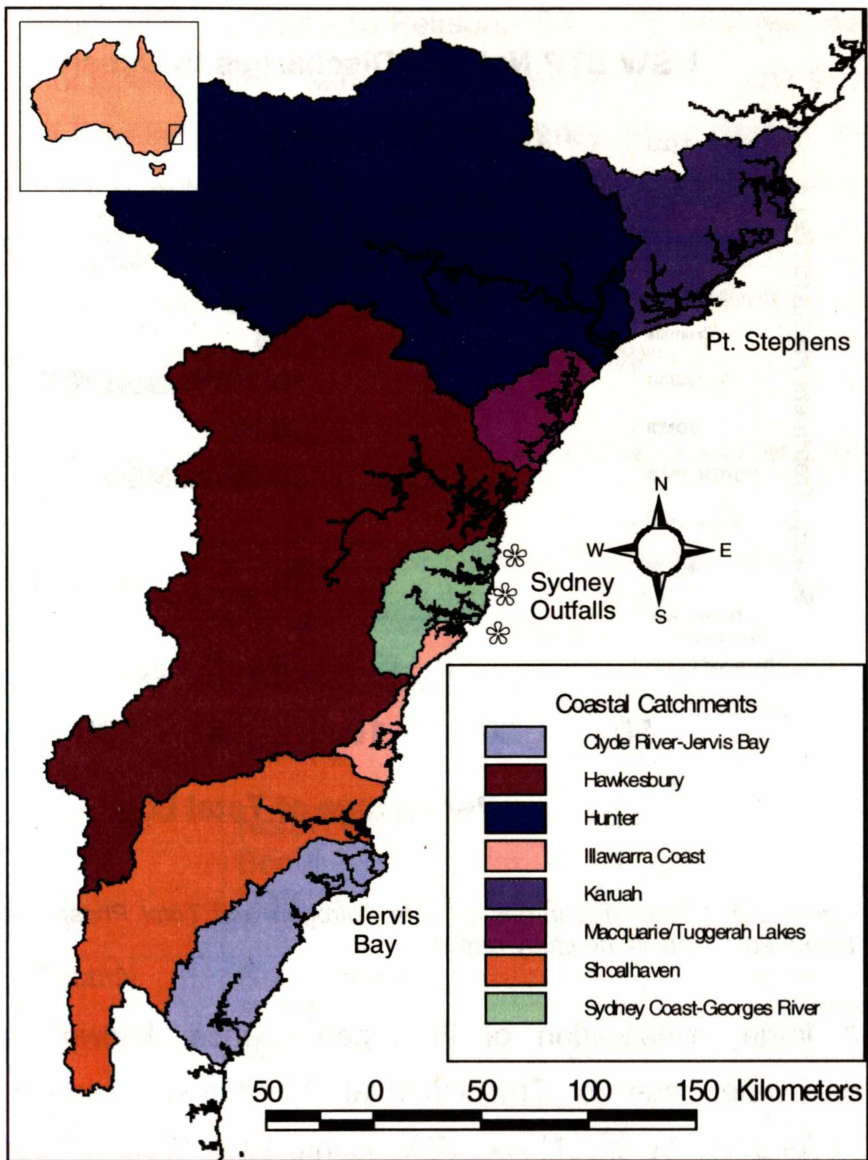


Figure 2-1. Map of the NSW coastal catchments between Port Stephens and Jervis Bay and the three major sewage outfalls off Sydney.

2-1-1 Sewage discharges to the Ocean

New South Wales discharges the majority of its treated sewage to the ocean, and over 80% of, most of it from the North Head, Bondi and Malabar deepwater outfalls off Sydney that were commissioned in 1991 (Figures 1-2 & 1-3). Figure 2-2 shows the comparative loads of effluent loads to the ocean from 33 outfalls located in the study region. These discharges represent the principal, continuous, anthropogenic source of nutrients deliberately discharged to NSW coastal waters.

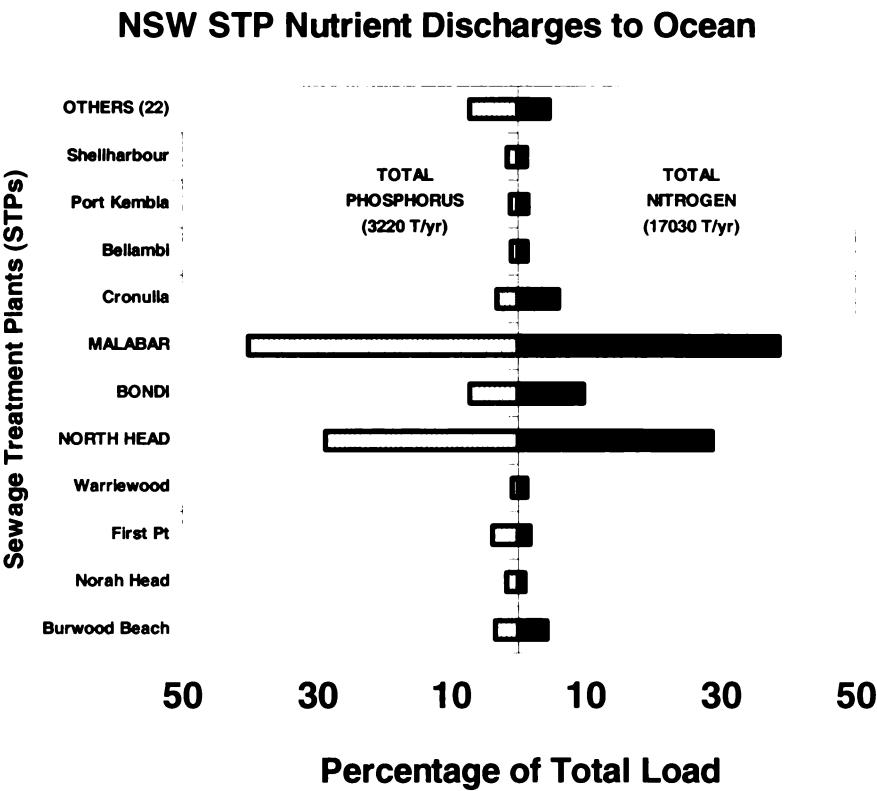


Figure 2-2: Ocean discharges of Total Nitrogen and Total Phosphorous from Sewage Treatment Plants in the study region.

A large investigation of their performance, known as the Sydney deepwater outfalls Environmental Monitoring Program (EMP), was undertaken by the NSW EPA during 1990-1993 (Wilson et al, 1995; Pritchard et al, 1995). The physical component of this program focussed on plume modelling and tracing experiments. The adopted near-field model, JETLAG (Lee and Hall 1994; Lee and Pritchard 1996; 1993; Lee and Cheung, 1990), used continuous time series records of ocean currents (the Ocean Reference Station, see section 2-2-1) and Sewage

Treatment Plant (STP) data to estimate initial effluent dilution, plume thickness, and plume centre line depth. The formulation of JETLAG tracks the evolution of the average properties of plume elements at various time steps by conservation of horizontal and vertical momentum, conservation of mass accounting for entrainment, and conservation of tracer mass. Sensitivity testing and comparisons with data obtained from plume tracing experiments conducted off Malabar indicated that JETLAG provided a good representation of plume behaviour (Lee and Pritchard, 1994; Pritchard et al, 1996; Cathers and Peirson, 1991). JETLAG was therefore used to compile a time series to represent plume characteristics immediately after initial momentum and buoyancy driven dilution. Table 2-1 lists the three outfalls performance and Average Dry Weather Flow Rates (ADWF) based modelling during the Sydney EMP. As part of the ONPP, this data was used to generate nutrient flux estimates into the coastal waters for comparison with other nutrient sources.

Table 2-1: Nutrient concentrations from the three main deepwater outfalls off Sydney.

Nutrient	Outfall	Effluent concentration mg/L	
		Median	Maximum
Ammonia N	North Head	32.0	37.0
	Bondi	27.0	37.0
	Malabar	30.0	36.0
NOx	North Head	<0.01	0.03
	Bondi	<0.01	0.35
	Malabar	<0.01	0.07
Total N	North Head	44.1	49.9
	Bondi	36.0	41.0
	Malabar	39.1	44.9
Total P	North Head	7.50	8.70
	Bondi	4.45	5.80
	Malabar	5.40	6.60
Flow (ADWF)	North Head	280ML/d	
	Bondi	130ML/d	
	Malabar	430ML/d	

Source: Sydney Water (1997)

2-1-2 Catchment monitoring

Load Assessments

A preliminary assessment of nutrient discharges from estuaries was undertaken by Sinclair Knight (1998) as part of the ONPP, compiling data on discharges from the eleven catchments that border the Port Stephens to Jervis Bay coastal region (see Figure 2-1). Of the eleven catchments that discharge to the coastal study region, Table 2-2 indicates that the Hawkesbury and Hunter catchments comprised ~70% of the total catchment area and ~50% of the total load.

Table 2-2. Catchment Area and Loads for coastal catchments between Port Stephens and Jervis Bay, given as average Total Nitrogen (Av.TN) and average Total Phosphorous (Av. TP).

Estuary River	Catchment Area (km2)	Av.TN load (tonnes/yr)	Av.TN export (tonnes/yr)	Av. TP load (tonnes/yr)	Av.TP export (tonnes/yr)
Port Stephens <i>Karuah</i>	4480	728	153	109	23
Newcastle Hbr <i>Hunter</i>	22020	1407	296	211	44
Lake Macquarie	749	120	25	18	4
Tuggerah Lake <i>Wyong</i>	802	206	43	7	1
Broken Bay <i>Hawkesbury</i>	21730	3018	634	174	36
Port Jackson <i>Parramatta</i>	620	500	105	53	11
Botany Bay <i>Georges/Cook</i>	1208	655	138	127	27
Port Hacking <i>Hacking</i>	230	21	4	3	1
Lake Illawarra <i>Macquarie Rivulet</i>	268	1973	241	53	11
<i>Shoalhaven</i>	7300	341	72	13	3
Jervis Bay	271	19	4	3	1

A shortcoming identified in the overview by Sinclair Knight (1998) was the lack of information on nutrient concentrations discharged to ocean waters during high rainfall events. Information within the report also indicated that the nutrient concentrations in the estuaries under “normal” conditions were similar to ambient ocean waters, and in particular markedly less than the concentrations in slopewater or the diluted effluent (at 1:1000) from the deepwater outfalls. It was therefore decided to focus on the Hunter and Hawkesbury catchments and aim to sample wet weather events from each, as a guide to assess the effect of such an event on the coastal environment. Utilising the Manly Hydraulic Laboratory river level gauge network (through restricted NSW EPA access), rainfall events were monitored to determine their influence in the lower catchment and hence discharge to the coastal ocean.

2-1-3 Wet Weather Event Studies

Hunter River

The Hunter catchment experienced a series of flood events that commenced in late July 1998 and continued through August. The initial flood had river levels at Singleton around 8m above normal. The Hunter River discharges through a narrow (~100m) entrance to the ocean. This well defined hydraulic constrictor provides a clear measuring point for waters discharged into the adjacent coastal seas. Three sampling stations were taken across this entrance concentrating on surface layers. Samples were taken at surface, 1m, 2m, 5m and 10m. The station on the southern side of the entrance was only 6m deep, so the 10m sample was substituted for one at 3m. Samples were taken on 29, 30 and 31 July 1998, with the flood peak passing out of the system on 30 July 1998. Figure 2-3 shows the sampling locations during the July 1998 flood event. Weather permitting depth profiles of samples were also taken at opportunistic offshore sites in an attempt to quantify the plume dimensions. At each station, continuous casts were taken by a Conductivity, Temperature & Depth (CTD) probe and water quality samples were made at specified depths throughout the water column to quantify a surface fresh layer and the intruding saline layer beneath.

Section 2-3-1 of this chapter should be referred to for detail on CTD specifications, calibration, and water quality sampling protocols and testing methods. The CTD collected information on temperature, salinity, depth, fluorescence, pH, dissolved oxygen and light transmissivity. Water quality samples were analysed for total and dissolved fractions of nitrogen and phosphorous, silica and total suspended sediments.

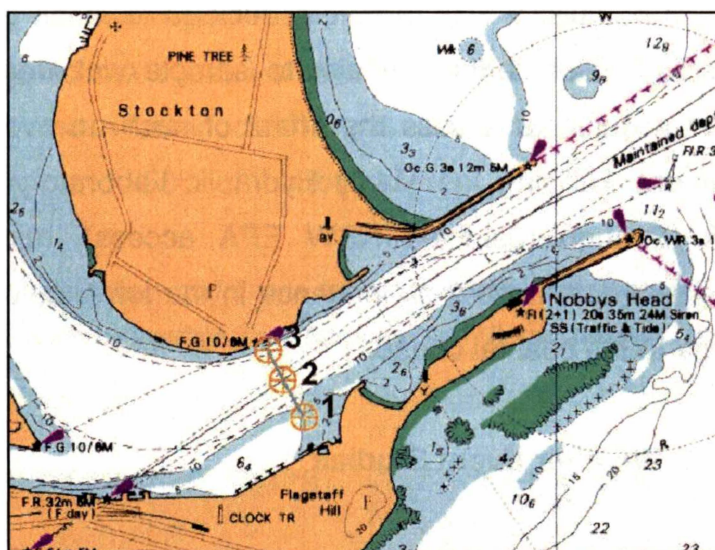


Figure 2-3. Sampling stations across the Hunter river during July 1998.

Hawkesbury River

The large estuarine section of the Hawkesbury catchment combined with a broad and complex ocean entrance, made it difficult to define a simple cross-sectional sampling transect to effectively define the discharge to the coastal ocean. Wolanski and Collis (1976) investigated the Hawkesbury during dry and wet weather events, and noted the dominance of the salinity profile mitigating seaward movement of freshwater during most flow conditions. With the cross-sectional area of the Hawkesbury channel decreasing exponentially with distance from the mouth, the saline “control” in the lower 30km dominates the dynamics in the system. Two intense coastal rain events (100-200mm) in the Hawkesbury catchment triggered pilot studies on 10 April 1998 and 6 May 1998, but measured little effect on the catchment discharge (river levels increased by 0.5m at Castlereagh (upper Hawkesbury catchment), upstream of Penrith). A larger event (>200mm occurring over most of the catchment) was surveyed between 10 August and 1 September 1998 where on two occasions the

Castlereagh levels increased 5-6m. Upstream and entrance sampling transects stations, as shown in Figure 2-4, were repeated throughout the flood event.

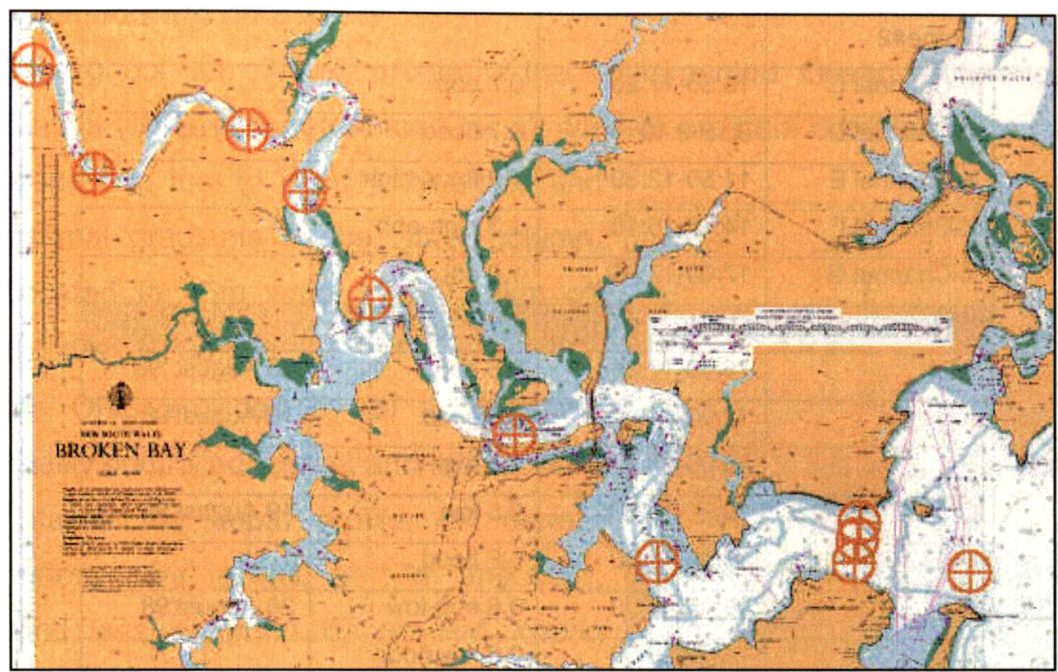


Figure 2-4. Sampling stations along the estuarine section of the Hawkesbury river during the wet weather event of July-August 1998

The upstream transect extended to 45km upstream from the entrance to monitor the dynamics of the salt wedge that dominates the estuary during normal flow conditions, and account for any changes in nutrient concentration due to sedimentation and/or erosion. Table 2-3 provides detail of sampling schedules, depths and locations. CTD and water quality sampling matched those taken during the earlier Hunter River flood event in late July 1998. Aerial photographs taken at the time of flooding for both systems show floodwaters clearly discharging into the coast waters (Figure 2-5).

Table 2-3 Sampling schedules for wet weather sampling at the Hunter and Hawkesbury River during July-September 1998.

Transect	Time	Tide (m)	Date
Hunter River			
X-Channel 1	10:45-11:30	1.3 flood-high	29 July'98
X-Channel A	9:30-10:45	1.0 flood	30 July'98

Offshore plume#1	12:00-13:10	1.35 high	
X-Channel B	13:56-14:25	1.3 high-ebb	
Offshore plume#2	15:45-17:19	1.0 ebb	
X-Channel C	16:30-17:20	0.8 ebb	
X-Channel D	9:12-9:40	0.7 flood	31 July'98
X-Channel E	11:50-12:30	1.3 flood-high	
X-Channel F	14:46-15:15	1.3 high-ebb	
X-Channel G	17:00-17:25	1.0 ebb	
Hawkesbury River			
Pilot	16:00-17:25	0.8 ebb	10 August '98
A	12:00-14:00	0.8 flood	18 August'98
B	16:00-17:30	1.5 high	
C	10:00-13:00	0.5 low	19 August'98
D	15:00-17:30	1.3 flood	
E	10:00-12:30	0.6 ebb-low	20 August'98
F	13:30-15:00	0.6 low-flood	
G	14:00-17:30	1.3 flood	
H	14:42-16:40	Flood	22 August'98
I	8:00-9:45	Flood	27 August'98
J	9:30-11:00	Flood	1 Sept'98



Figure 2-5: Aerial photographs showing estuarine discharge to coastal waters during the flood events on the Hunter (left) and Hawkesbury (right) rivers in July/August 1998.

2-2 OCEANIC PROCESSES

2-2-1 Current Moorings

ORS mooring off Sydney

Throughout the 3-year program, the instrumented Ocean Reference Station (ORS) was referenced for all oceanic program components as a monitoring tool to identify dynamics and thermal gradients in the water column. Located in 65m water depth ~3km off Bondi (33° 53.733' S; 151° 18.955' E), the ORS provided 5, 60 and 720min quality controlled current and temperature data in the depth profile. S4 current meters were located at 17m and 52m, wind was recorded by an RM Young anemometer located 5m ASL on the buoy, and temperature data was recorded by 16 Aanderaa thermistors strung from below the buoy to the 52m current meter.

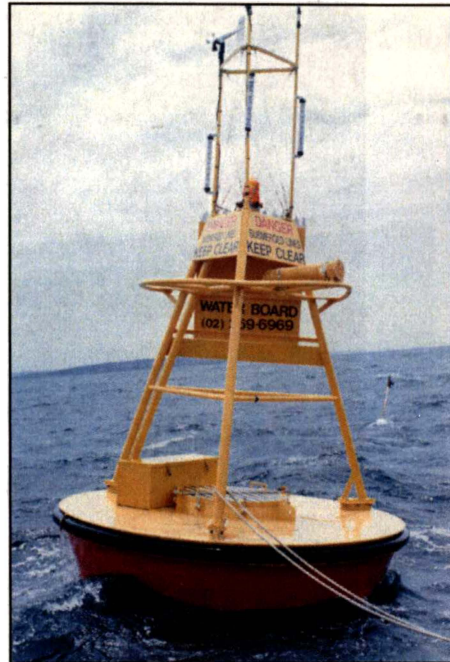


Figure 2-6: The Ocean Reference Station located ~3km off Bondi, Sydney in 65m water, providing real-time current, temperature and wave data during the ONPP.

The current meters were calibrated to measure currents (accuracy 0.01m.s⁻¹ and +/-0.5°), temperature (0.02°C) and depth (0.15%). The anemometer performed to the manufacturer's specifications of 0.01m.s⁻¹ and +/-1° for velocity and direction respectively. Thermistors similarly matched the quoted 0.1°C specifications. Further detail of this facility, which has been in operation by Sydney Water since July 1989, can be found in Lawson and Treloar (1993). This long continuous record provided an invaluable insight to a wide temporal range of forcing parameters in the coastal ocean. Figure 2-6 shows the surface buoy of the ORS, and Figures 1-2 & 2-9 locate this facility in the study region.

S4 mooring off Port Stephens

A review of NOAA SST imagery and transect work from the 1995/96 season indicated upwelling dynamics were often present as the EAC stream flow passes south of the Port Stephens prominence (Point Stephens), suggesting this to be an interesting site for a current mooring.

An S4P current meter at Port Stephens (denoted as PS03) was deployed



between 26 November'96 and 20 February'97 at 59m in 61m water off Boat Harbour ($32^{\circ} 50.60'S$, $152^{\circ} 04.73'E$), recording 5 min averages every 30 mins. The equipment was similarly calibrated to the S4P's at the ORS. Figure 2-7 shows the S4P mooring prior to deployment off Port Stephens in late 1996, and Figure 2-9 locates this facility in the study region.

Figure 2-7: The S4P current meter, mooring line and acoustic release set prior to deployment off Port Stephens in November 1996.

ADCP mooring off Port Stephens

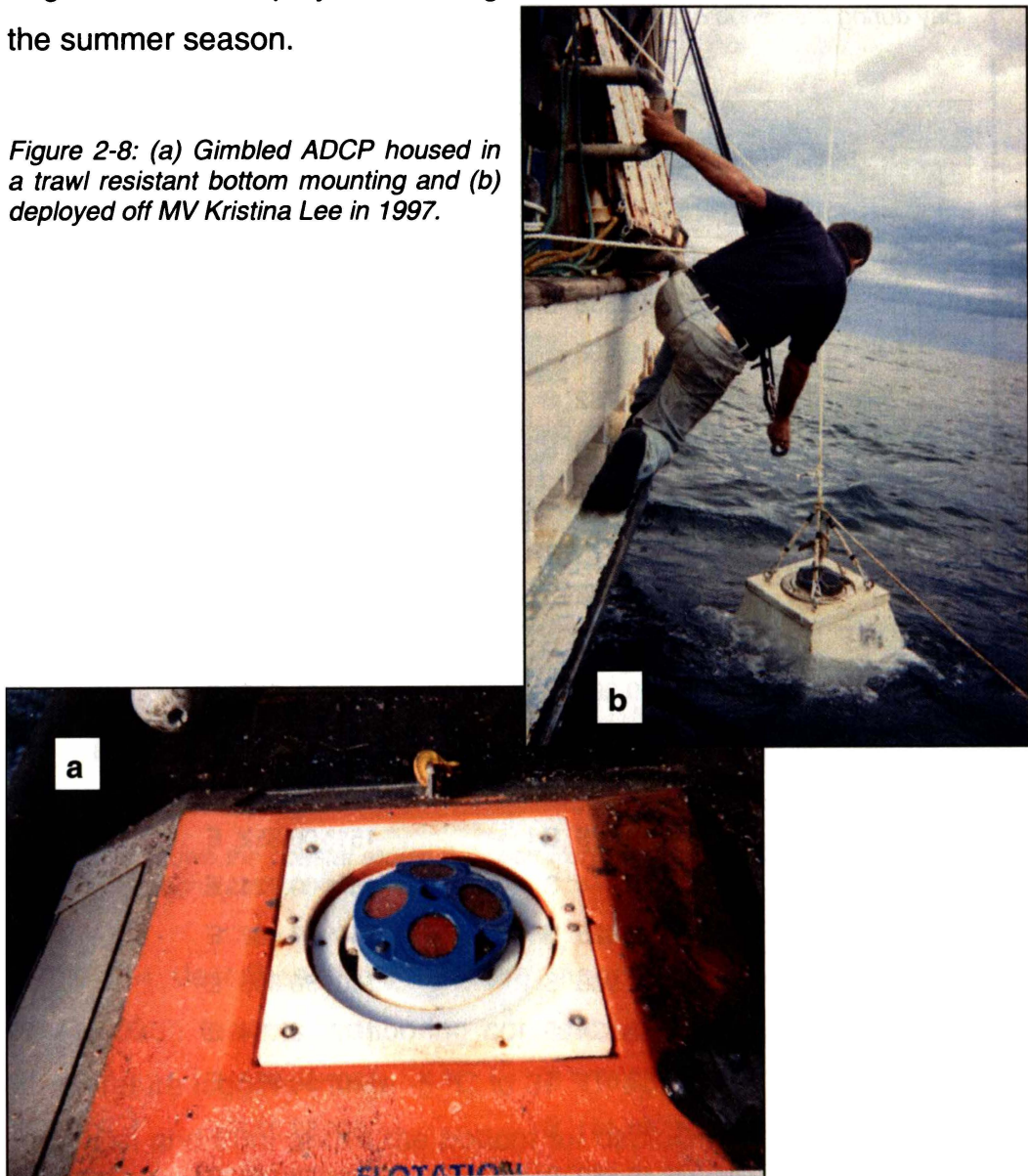
For continuity a 300KHz RD Instruments Acoustic Doppler Current Profiler (ADCP) was deployed during the thermistor array campaign at the same location off Port Stephens (PS03) in the following summer season to the 1996/97 S4 current mooring deployment.

The ADCP is a state-of-the-art instrument that utilises the Doppler effect by transmitting sound at a fixed frequency and listening to echoes returning from sound scatterers in the water. These sound scatterers are small particles or plankton that reflect the sound back to the ADCP. When sound scatterers move toward the ADCP, the sound heard by the scatterers is Doppler-shifted to a higher frequency. The amount of this shift is proportional to the relative velocity between the ADCP and scatterer. The degree of backscatter in the return signal is also a useful guide to particulate concentration, and is therefore able to qualify

planktonic activity in the water column in conjunction with other water parameters being measured.

The ADCP was gimbled in a trawl-proof bottom mounting at 60m depth (Figure 2-8a), and sampled 1m depth-averaged bins every 15 minutes. The 15-minute sample was represented as an ensemble of 60 transmitted pings, which provided a current speed accuracy with a standard deviation of 2.2cm/s. The system was deployed on 2 October 1997 (Figure 2-8b) and retrieved for servicing on 4 December 1997. Failure of the recovery system and heavy fouling required the housing to be re-built, which negated further deployment during the summer season.

Figure 2-8: (a) Gimbled ADCP housed in a trawl resistant bottom mounting and (b) deployed off MV Kristina Lee in 1997.



2-2-2 1997/98 Thermistor array

Twenty thermistor moorings were deployed between Port Stephens and Jervis Bay during the period of July 1997-August 1998, to characterise the frequency and duration of slope water intrusions to the inner shelf. All instrumentation was located along the inner continental shelf, in water depths of 50-100m. A zig-zag deployment pattern, was selected to assist in determining the directional propagation of major events. The mooring locations, water depths and example temperature logger are shown in Table 2-4 and in the map in Figure 2-9.

Table 2-4. Location of thermistor mooring deployed between Port Stephens and Jervis Bay during the period of July 1997-August 1998.

Mooring Location	Latitude (WGS84)	Longitude (WGS84)	Water depth (m)
PS01	33°00.438' S	151° 53.977' E	95
PS02	32° 40.558' S	152° 17.947' E	61
PS03	32° 50.498' S	152° 04.846' E	59
PS04	32° 54.752' S	152° 01.352' E	90
PS05	32° 57.019' S	151° 57.591' E	91
PS06	32° 55.360 S	151° 56.339' E	54
PS07	33° 15.896 S	151° 45.582' E	98
BB01	33° 53.733' S	151° 18.955' E	66
PH01	34° 05.379' S	151° 11.985' E	60
PH02	34° 09.300' S	151° 08.289' E	60
PH03	34° 10.611' S	151° 10.204' E	100
PH04	34° 16.895' S	151° 04.721' E	64
PH05	34° 19.023' S	151° 06.352' E	96
PH06	34° 28.444' S	151° 00.921' E	78
JB01	35° 07.425' S	150° 47.088' E	50
JB02	35° 04.965' S	150° 50.805' E	78
JB03	34° 56.324' S	150° 53.434' E	52
JB04	34° 52.679' S	150° 56.953' E	100
JB05	34° 48.441' S	150° 52.372' E	60
JB06	34° 43.562' S	150° 57.193' E	95

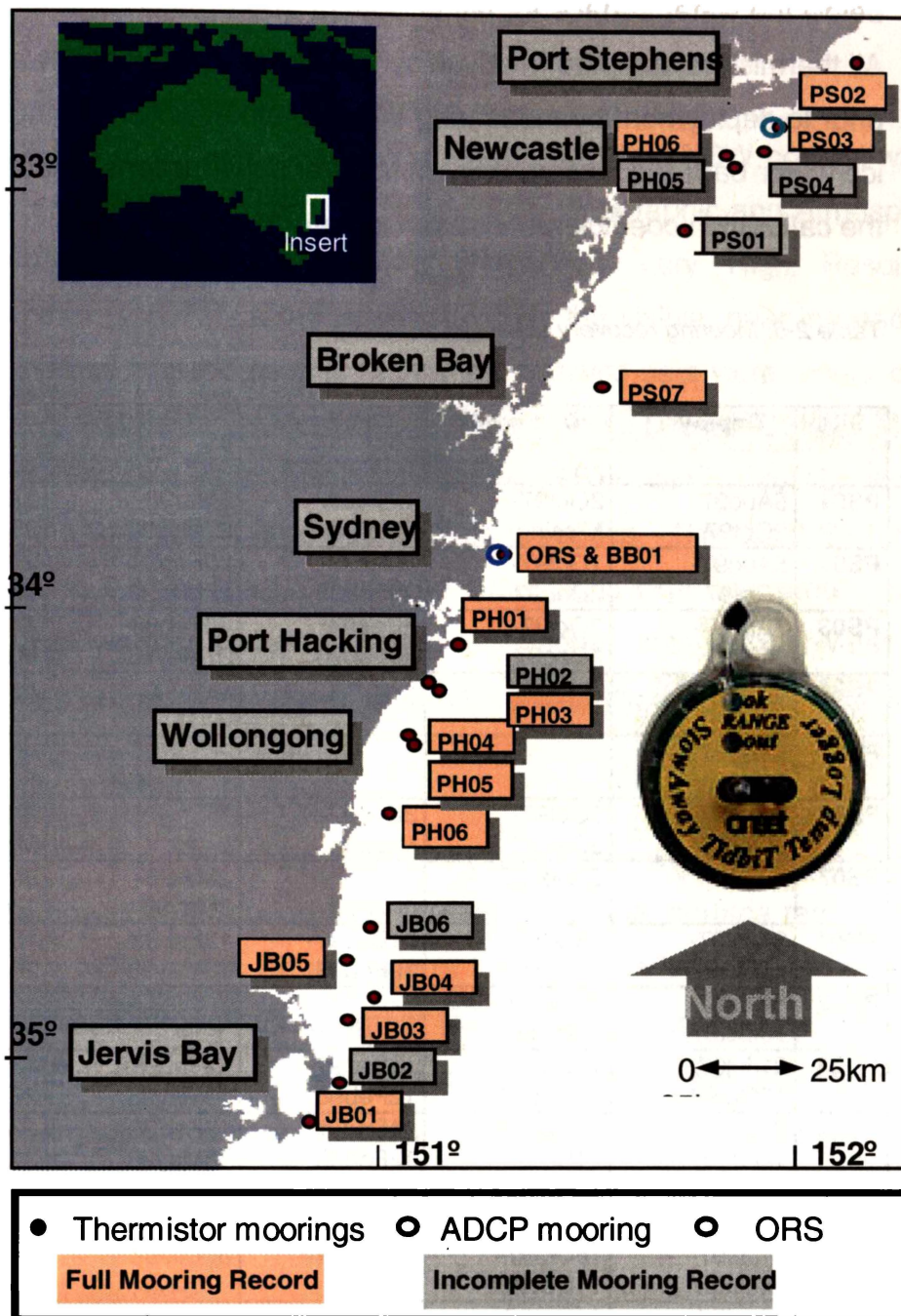


Figure 2-9 shows the coastal region between Port Stephens and Jervis Bay. The specific mooring locations are marked.

Table 2-4 describes the respective mooring deployment and recovery times. Each thermistor mooring consisted of three ONSET StowAway© temperature loggers (range -5 °C to 37 °C; accuracy 0.1 °C), positioned at 2m, 10m and 20m above the bottom for deployments #1, #2 and #3. For deployments #4 and #5, two additional thermistors were included in the mooring, positioned at 10m below the water surface and 20m or 50m

below the water surface for either 50m or 100m water depths respectively. All thermistors sampled hourly in synchronicity. Each logger was calibrated prior to deployment by measuring the zero offset whilst logging in a sealed ice/water bath (according to manufacturer's instructions). Appendix 2 lists the calibration coefficients for each logger.

Table 2-5: Mooring recovery schedule.

Site	Deploy #1	Deploy #2	Deploy #3	Deploy #4	Deploy #5
PS01	5Aug97- 2Oct97	2Oct97- Missing	12Dec97- 3Mar98	3Mar98- 27May98	27May98- 8Sep98
PS02	5Aug97- 1Oct97	1Oct97- 2Dec97	2Dec97- 20Feb98	20Feb98- 27May98	27May98- 8Sep98
PS03	5Aug97- 2Oct97	2Oct97- 2Dec97	2Dec97- 20Feb98	20Feb98- 27May98	27May98- Missing
PS04	5Aug97- Missing				
PS05	5Aug97- Missing				
PS06	6Aug97- 2Oct97	2Oct97- 3Dec97	3Dec97- Missing		27May98- Missing
PS07		21Nov97-	- 3Mar98	3Mar98- 8May98	8May98- 13Oct98
PH01	31Jul97- 15Oct97	15Oct97- 11Dec97	11Dec97- 12Feb98	12Feb98- 13May98	13May98- 26Aug98
PH02	31Jul97- 15Oct97	15Oct97- Missing			
PH03	31Jul97- 15Oct97	15Oct97- 11Dec97	11Dec97- 12Feb98	12Feb98- 13May98	13May98- 26Aug98
PH04	31Jul97- 15Oct97	15Oct97- 11Dec97	11Dec97- 12Feb98	12Feb98- 13May98	13May98- 31Aug98
PH05	31Jul97- 15Oct97	15Oct97- 11Dec97	11Dec97- 12Feb98	12Feb98- 13May98	13May98- 31Aug98
PH06	31Jul97- 15Oct97	15Oct97- 11Dec97	11Dec97- 3Feb98	3Feb98-	- 31Aug98
JB01	26Jul97- 14Oct97	14Oct97- 12Dec97	12Dec97- 3Feb98	3Feb98- 28Apr98	28Apr98- Missing
JB02	26Jul97- Missing				
JB03	26Jul97- 14Oct97	14Oct97- 12Dec97	12Dec97- 3Feb98	3Feb98- 28Apr98	28Apr98- 11Aug98
JB04	26Jul97- 14Oct97	14Oct97- 12Dec97	12Dec97- 3Feb98	3Feb98- 28Apr98	28Apr98- 11Aug98
JB05	26Jul97- 14Oct97	14Oct97- 12Dec97	12Dec97- 3Feb98	3Feb98- 28Apr98	28Apr98- 11Aug98
JB06	26Jul97- Missing			3Feb98- Missing	

2-2-3 Satellite Imagery

NOAA Sea Surface Temperatures

Surveillance of oceanic circulation patterns affecting NSW coastal waters was based on images from the National Oceanographic and Atmospheric Administration (NOAA) series of Advanced Very High Resolution Radiometer (AVHRR) satellites which sense the visible, near infrared and three thermal infrared wavelength bands. Satellite data were received and corrected (atmospheric, radiation pressure, etc) by the CSIRO Marine Laboratories for sea surface temperature (SST) using a combination of two of the thermal infrared bands. This produces ~1km pixel SST maps accurate to 0.1°C. The SST inferred circulations were interpreted on the basis that warmer water is dynamically higher than cooler water thus promoting movement down thermal gradients with Coriolis effects deflecting the flow to the left.

NOAA SST images were regularly checked (daily-weekly) and cloud-free images downloaded during the program to monitor surface temperatures along the NSW coast. An average of five downloaded images per month were collated through the program for routine monitoring, and increased during field campaigns to ~ten per month. Imagery was processed with ERDAS Imagine software and prepared in ARCVIEW for reports. Examples of SST imagery are shown in Chapter 4 and 5.

SeaWiFS imagery

Ocean colour can typically vary from the dark green of some phytoplankton rich (eutrophic) estuarine waters, to the deep blue of oligotrophic East Australian Current waters. Satellite mounted ocean colour sensors take advantage of these variations in ocean colour and use algorithms to estimate chlorophyll pigments and indicate primary production.

The first ocean colour satellite sensor, the Coastal Zone Colour Scanner (CZCS), was launched over two decades ago. Data from this experimental satellite sensor revolutionised the understanding of phytoplankton

distributions and dynamics, both at a global scale and in the seas around Australia (Parslow, 1999). Coastal water colourations however challenged the resolution of the CZCS with estuarine plumes, anthropogenic discharges, and re-suspended sediments introducing various hues of grey, brown and yellow to the spectrum. The colour scanners on more recent satellite launches have been designed to provide the increased spectral and spatial resolution needed to deal with the complicated optical signal of coastal waters (Parslow, 1999).

Our project focused on Sea-viewing Wide Field-of view Sensor (SeaWiFS) data for NSW coastal waters accessed via CSIRO Hobart. The SeaWiFS satellite was launched on 1 August 1997 as the operational successor to the CZCS which ceased operation, well beyond its design life, in June 1986. SeaWiFS is a cooperative project between NASA and Orbital Sciences Corporation, which aimed at obtaining accurate ocean colour data from the world's oceans (to within 5%) for a 5 year period through algorithm development and a wide-ranging coordinated calibration program. Access to the data set is available through the web site at <http://seawifs.gsfc.nasa.gov/SEAWIFS.html>

The sensor has 8 channels ($412 < \lambda < 865\text{nm}$) with improved resolution (w.r.t. CZCS) to better delineate yellow (dissolved organic) substances, and better characterise aerosol contributions for atmospheric corrections. The satellite travels on a sun synchronous polar orbit (14 per day with 2806km swath), scanning the globe ~every 2 days at a maximum pixel resolution of 1.1km. The sensor typically estimates chlorophyll that relates to the upper 10-15m of the water column, however these may be compromised or prohibited by factors such as cloud cover, sun glint and terrigenous & dissolved organic matter in water. Discussion on the factors effecting the quality of chlorophyll estimates from SeaWiFS are developed further within section 8-3-1 of the discussion chapter.

Given the uncertainties associated with coastal waters, the SeaWiFS chlorophyll estimates were 'ground-truthed' within the study region, and provided to the CSIRO supplier for addition to the global calibration

database. During the weekly monitoring at sites off Port Hacking at sites CSIRO PH50 and PH100 (5-2, and Ajani et al., 2001) samples were collected from surface waters and from at depth of 10m. All spatially and temporally coincident data were compared for the period from September 1997 to March 1998. Most SeaWiFS data available for this comparison were non-optimal especially at the inshore site (PH50) where all comparable SeaWiFS data were non-optimal. That is, factors such as stray light, missing atmospheric data and sun glint usually compromised the estimation of chlorophyll concentrations. Because of this, and the uncertainty associated with near-coincident sampling, we also considered the eight SeaWiFS pixels (1km x 1km) surrounding the pixel corresponding to the sampling site.

Table 2-6: Comparison of SeaWiFS estimates with sampling at PH50 & 100m sites.

Date	SeaWiFS*			IN SITU**	
	Available data (pixels/9)	Mean Chlorophyll ($\mu\text{g/L}$)	Standard Deviation ($\mu\text{g/L}$)	Chlor. @ 0m ($\mu\text{g/L}$)	Chlor. @ 10m ($\mu\text{g/L}$)
PH50					
10/9/97	1/9	0.9	<i>n/a</i>	1.7 (2.1)	1.6 (2.0)
29/12/97	7/9	0.5	0.2	0.4 (0.4)	0.6 (0.5)
20/01/98	5/9	0.8	0.4	0.7 (0.8)	1.0 (1.1)
22/01/98	6/9	0.6	0.3	0.5 (0.6)	0.3 (0.6)
27/01/98	4/9	0.1	0.2	0.3 (0.3)	0.3 (0.4)
29/01/98	1/9	0.4	<i>n/a</i>	0.3 (0.4)	0.5 (0.6)
03/02/98	3/9	0.9	0.1	0.7 (0.8)	0.8 (0.8)
17/03/98	6/9	0.6	0.2	0.2 (0.2)	0.3 (0.3)
PH100					
10/09/97	9/9	0.9	0.2	1.3 (1.5)	1.4 (1.6)
25/11/97	2/9	0.6	0.0	0.2 (0.4)	0.3 (0.5)
02/12/97	6/9	0.2	0.2	0.3 (0.4)	0.4 (0.4)
29/12/97	7/9	0.1	0.1	0.3 (1.3)	0.3 (0.3)
13/01/98	5/9	0.7	0.7	0.9 (0.9)	1.1 (1.0)
20/01/98	5/9	0.9	0.8	0.6 (0.5)	1.8 (2.0)
22/01/98	9/9	0.4	0.2	0.2 (0.4)	0.9 (0.9)
27/01/98	9/9	0.2	0.04	0.3 (0.3)	0.3 (0.4)
29/01/98	9/9	0.2	0.1	0.2 (0.2)	0.4 (0.6)
03/02/98	2/9	0.5	0.1	0.3 (0.4)	0.5 (0.5)
25/02/98	7/9	0.2	0.04	0.3 (0.3)	0.4 (0.4)
11/03/98	2/9	0.03	0.00	0.1 (0.1)	0.2 (0.1)
17/03/98	7/9	0.1	0.03	0.2 (0.2)	0.2 (0.1)

* Values in italics indicate >1/2 available pixels delivered sub-optical estimates

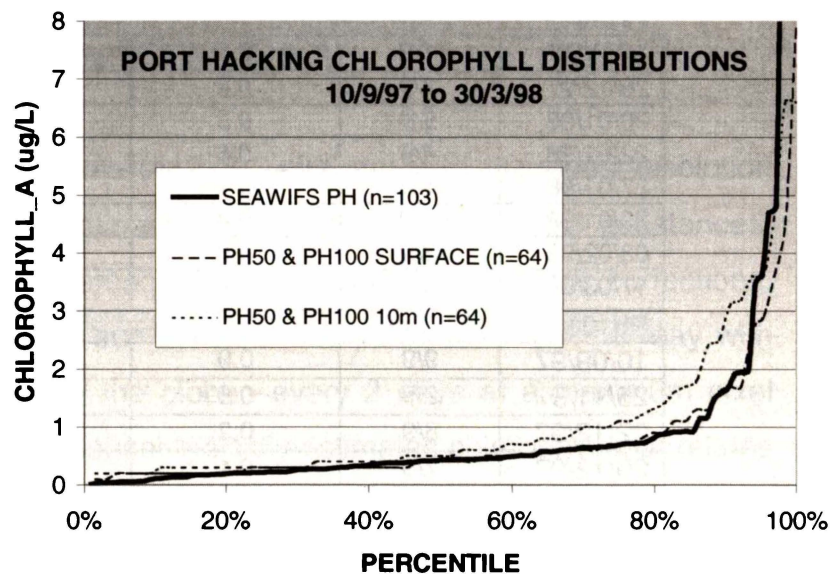
** HPLC (Spectrophotometry) laboratory determinations

SeaWiFS data were available in one or more of the 9 pixels for only 8 (PH50) and 14 (PH100) of the 32 *in situ* sampling occasions, as shown in Table 2-6. Arithmetic means (& standard deviations) were calculated from all available pixels for each of these occasions/sites. When SeaWiFS data were plotted against *in situ* data, a non-linear correlation was observed with SeaWiFS generally under estimating chlorophyll levels at both 0m and 10m, especially for high levels of chlorophyll. The relationships between SeaWiFS estimates and *in situ* determinations were generally better at the offshore site (PH100) than at the inshore site (PH50) (R^2 values ranged from 0.48 to 0.79) while correlations with SeaWiFS data were comparable at 0m and 10m depths. These findings were not surprising given the high proportion of sub-optimal or absent SeaWiFS estimates at PH50 and the high degree of mixing in the upper layer.

The overall distribution of all SeaWiFS data collected at the PH50 and PH100 sites was compared with the distribution of the entire *in situ* data set for the period

from September 1997 to March 1998 (i.e. irrespective of simultaneous acquisition).

Figure 2-10: SeaWiFS calibration using *in-situ* chlorophyll-a measurements from the Port Hacking stations (PH50& PH100).



Distributions in Figure 2-10 suggest that with available data, the current SeaWiFS algorithm provides reasonable estimates of 50 and 80 percentiles but the upper 10% of the surface water distribution ($>6\mu\text{g/L}$) is overestimated by SeaWiFS.

Images were collected during the Port Hacking responsive event (see Chapter 5-3-2) during January 1998, and for the Wet Weather studies (refer to section 2-1-1) during August 1998.

2-2-4 CSIRO sourced data

The Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Centre for Marine Studies is based in Hobart, Tasmania, and represents the principal marine research group in Australia. They were resourced during the ONPP for access to their archived hydrographic cruise data and a coastal subset of their regional empirical ocean model.

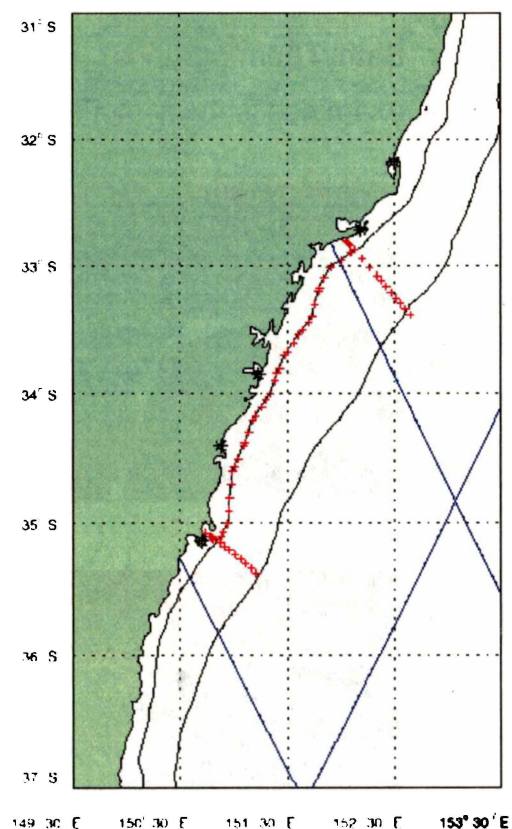
Cruise data

Hydrographic and water quality data from CSIRO cruises off east coast of Australia (back to 1965) between 31 and 36°S, was obtained from the CSIRO database (www.csiro.marine.au) as a reference of source slopewater to compare against slopewater observed during the shelf transects in 2-3 and 2-4. Quality controlled parameters for temperature salinity, pressure, nitrate, nitrite, dissolved phosphorous, and silica were retrieved for cross-analysis.

Simulation model results

The NSW EPA commissioned the CSIRO to run a multivariate linear regression model, developed for their CARS (Climatology of Australian Regional Seas) project, to infer along-shelf thermal structure within the study region. The model produced a 10-day repeat time series of temperature covering the period from October 1992 to July 1997.

Figure 2-11: Topex/Poseidon altimeter tracks (blue) and coastal sea level stations (black) used with SST imagery to simulate transects (red) of thermal structure in the study region.

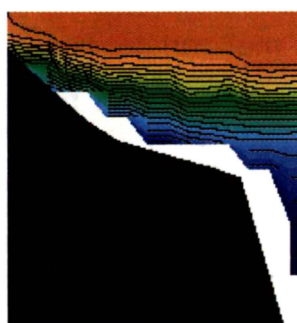
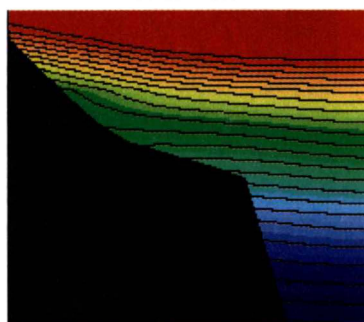


The simulated temperature field from CSIRO's empirical model incorporated SST data, Topex/Poseidon satellite altimeter data and coastal sea level data from tide gauges in Jervis Bay, Wollongong, Sydney and Point Stephens (Figure 2-11), and interpolated them into a 0.1° grid (Ridgeway, 1996, Ridgeway et al, 1997).

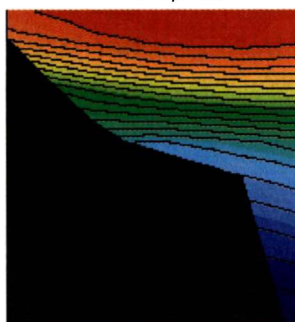
The model is based on the fact that in the Tasman Sea surface height is highly correlated with sub-surface temperature structure. The core of this model uses some 175 cycles of geophysical data records from the Topex/Poseidon mission (Oct'92-July-97), which produce altimeter heights with 6.2km alongtrack sample footprints, but with between track spacing of some 300km, therefore requiring supporting coastal sea level data and optimal interpolation to produce a regular grid. Whilst the sea level heights are accurate to within a few centimetres, the unknown geoid (the equipotential surface of the gravity field) needs to be subtracted to produce sea level anomalies, and hence infer a relative time varying internal structure. The authors estimate the mean steric height from CARS fields of mean temperature and salinity. Calibrations of this method were made against the cruise data, SST imagery and XBT (eXpendable BathyThermographs) records which formed the basis of CARS. The examples shown in Figure 2-12 show the mixed layer and thermocline



14-Jan-1994



14-Apr-1994



gradient are well represented, although the extent of cold-water intrusions onto the shelf appears underestimated.

Figure 2-12: Cross-section of data slices taken by RV Franklin from CTD observations at 34°S in during January and April 1994 (top panels) and the CSIRO data assimilation model results for corresponding dates (from Ridgeway and Dunn, 1998).

As the cold-water intrusions are of great interest for this study, the entire model data set is calibrated against the continuous times series temperature structure measured at the ORS.

2-3 OCEANIC NUTRIENTS

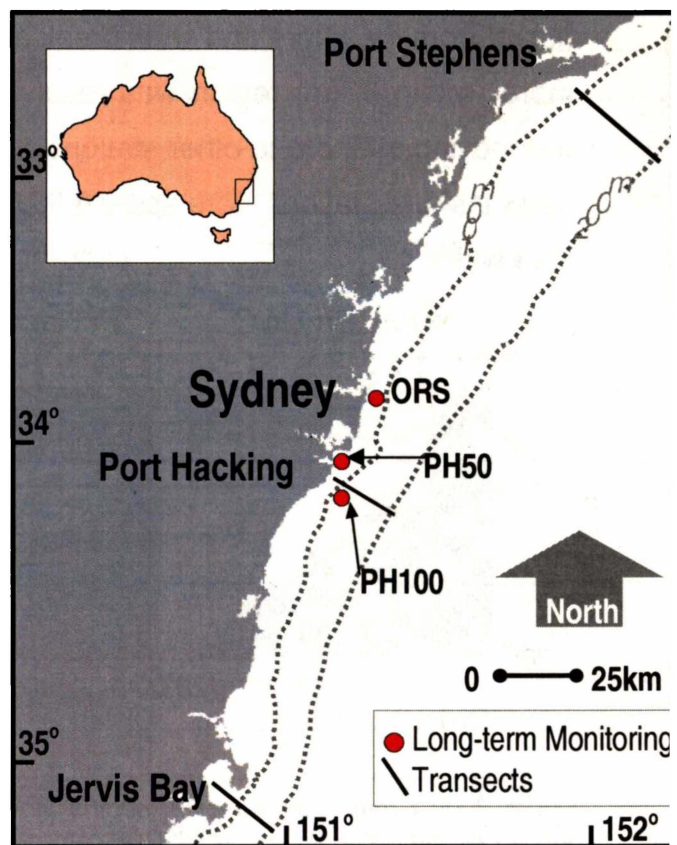
2-3-1 Routine transect sampling in Australia

The aim of this study component was to characterise ambient nutrient concentrations and more specifically, identify the extent and associated nutrient concentrations of slope water intrusions and upwellings, so that this information can be related to phytoplankton growth in the NSW coastal waters (from Port Stephens to Jervis Bay).

Site Selection

The emphasis of the program was placed on the heavily populated coastline between Port Stephens and Jervis Bay, with additional focus beyond this region based upon areas of natural physical significance (e.g. prominent upwelling sites).

Figure 2-13: Locality map showing sampling stations, transects and instrument moorings used in the investigation along a 300km stretch of the Australian eastern seaboard.



Port Stephens and Jervis Bay were selected as they are adjacent to Sydney, they have a history of slope water upwelling and bloom events but they do not appear to be associated with local anthropogenic nutrient sources.

From Sea Surface Temperature (SST) satellite imagery, the coastal region around Port Stephens is frequently influenced by a strong southward streaming EAC flow, and the rapid change in coastline orientation often promotes backflow in the lee of this topographic change. Placed further south in the Tasman Sea, the region around Jarvis Bay experiences infrequent impacts by a dissipating turbulent EAC eddy field. However, as the bay entrance is some 10 kms offshore of the general NSW coastline orientation and the shelf break less than half the distance at Port Stephens, this section of coastline has an almost linear drop-off to the shelf break ie. little or no flat mid-shelf region. As a result it is often prone to the dynamics of oceanic circulations in the Tasman Sea.

Three transects located at Port Stephens, Port Hacking and Jarvis Bay are shown in Figure 2-13. Stations along these transects were spaced equidistant from the shore and shelf break as shown in Figure 2-14. The near-shore (within 5 km) region was resolved by starting at the 20m contour and moving offshore to other stations 1, 2 and 2 km apart. From the shelf break inshore stations were spaced 5 km or 10 km apart depending on the shelf width.

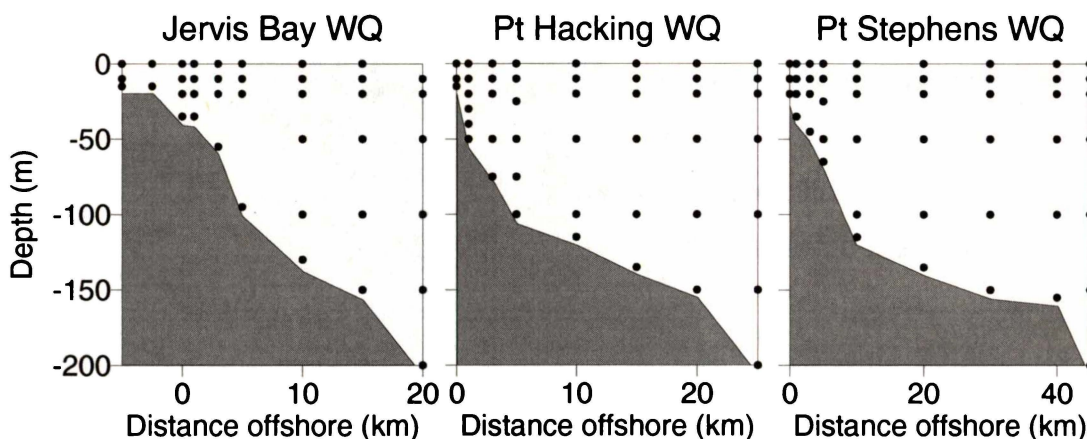


Figure 2-14: Cross-shelf sampling depths along the Port Stephens, Port Hacking and Jarvis Bay transects during the 1995-98 campaign.

Figure 2-14 details the water quality sampling along the transect. Transect lines for Port Stephens, Port Hacking and Jarvis Bay are 45 km, 25 km and 20 km respectively. Jarvis Bay has extra stations located 2.5 and 5

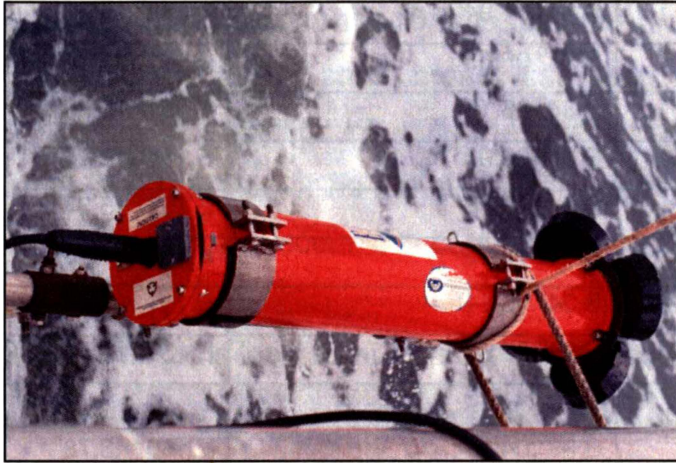
km inshore of the entrance to the Bay. This was to monitor oceanographic and nutrient conditions within the Bay. GPS coordinates for each station along each transect are given in Table 2-7.

Table 2-7 GPS Coordinates for stations along the Port Stephens, Port Hacking and Jervis Bay transects during the 1995-98 campaign.

TRANSECT: Port Hacking		
Station 1 (25m)	S 34° 04.94'	E 151° 10.79'
Station 2 (66m)	S 34° 05.35'	E 151° 11.35'
Station 3 (84m)	S 34° 06.15'	E 151° 12.28'
Station 4 (105m)	S 34° 06.98'	E 151° 13.14'
Station 5 (130m)	S 34° 08.88'	E 151° 15.37'
Station 6 (140m)	S 34° 10.85'	E 151° 17.78'
Station 7 (145m)	S 34° 13.14'	E 151° 19.94'
Station 8 (200m)	S 34° 15.92'	E 151° 22.76'
TRANSECT: Jervis Bay		
Station 1 (24m)	S 35° 04.21'	E 150° 43.78'
Station 2 (40m)	S 35° 05.68'	E 150° 46.62'
Station 3 (40m)	S 35° 06.08'	E 150° 47.09'
Station 4 (56m)	S 35° 06.73'	E 150° 48.21'
Station 5 (95m)	S 35° 07.34'	E 150° 49.25'
Station 6 (128m)	S 35° 08.88'	E 150° 52.01'
Station 7 (130m)	S 35° 10.33'	E 150° 54.76'
Station 8 (230m)	S 35° 11.81'	E 150° 57.45'
TRANSECT: Port Stephens		
Station 1 (20m)	S 32° 48.095'	E 152° 02.950'
Station 2 (30m)	S 32° 48.773'	E 152° 03.605'
Station 3 (40m)	S 32° 49.684'	E 152° 04.432'
Station 4 (65m)	S 32° 50.451'	E 152° 05.354'
Station 5 (100m)	S 32° 57.454'	E 152° 07.614'
Station 6 (130m)	S 32° 56.673'	E 152° 11.909'
Station 7 (138m)	S 33° 00.734'	E 152° 16.158'
Station 8 (150m)	S 33° 04.757'	E 152° 20.354'
Station 9 (200m)	S 33° 07.273'	E 152° 22.770'

Instrumentation

An RD Instruments 300KHz Broadband Acoustic Doppler Current Profile (ADCP) collected current velocity profiles along the predetermined transects. It has similar specifications and principle of operation (see section 2-2-1) as the Workhorse 300KHz ADCP used in the PS03 mooring off Port Stephens in 1997, except that this instrument is also



capable of detecting and tracking the sea floor, enabling it to bottom track whilst determining velocity profiles (ie able to subtract the boat velocity from the net velocity measured to produce a transect of current profiles).

Figure 2-15: A 300KHz ADCP deployed during the field campaigns.

The ADCP was deployed off the gunwhale of a monohull or the stern catamaran hulled vessel with the transducer head typically located at 0.5m below the water surface (see Figure 2-15). The instrument was configured to sample continuously at 20 pings per ensemble resolving in 2m depth bins to ~160m depth. These settings resolved a surface bin at 3m depth at an ensemble interval of 25 seconds, and measured currents to a standard deviation of 0.63cm/s. ADCP transects were only undertaken when swell/seas were 1m or less to ensure data reliability. For the summer sampling periods (1995-1997) the ADCP was routinely employed along transects. A major system overhaul during mid-late 1997 prevented its use in the final season.

At stations along the transect, a profiling Conductivity, Temperature & Depth (CTD) probe, was deployed (see Figure 2-16). The employed SEABIRD SBE25 Sealogger CTD, logs at 8Hz and has respective conductivity, temperature and pressure accuracy (resolution) of 0.0003

(0.00004S/m), 0.004 (0.0003)°C and 1.25 (0.75)m. This instrument was coupled with a Chelsea Instruments Fluorometer (0.01µg/L), Seabird dissolved oxygen and pH sensor, and a Seatech 25 cm pathlength Transmissometer.

Figure 2-16: CTD deployed from NSW EPA vessel RV Aquilla in Jervis Bay, NSW.

The temperature, conductivity, and dissolved oxygen were constantly pumped in-line providing a constant flow regardless of the instruments profiling speed. The temperature and conductivity sensors were also ducted to ensure a constant offset with respect to their relative response times.



During periods of maintenance, a Seabird 911plus CTD was used. Whilst this 24Hz instrument runs the same conductivity, temperature and pressure sensors to greater accuracy, it was not configured with a fluorometer, pH or dissolved oxygen sensors, and therefore remained as the back-up unit during the study. Instrument deployments routinely followed Seabird protocols (e.g 90 sec delay at the surface prior to profiling to ensure equipment equilibrates with ocean waters). A marked deployment cable provided a guide for CTD deployments, which were taken to within 2m of the bottom depth indicated from the onboard echo sounder. Sensor maintenance ensured routine soaking in distilled water of all pumped sensors, pH sensor soaking in pH 4 buffer solution, and fluorometer lens protective placed during and between field campaigns. Data was processed using Seasoftware for pressure reversals, wild point editing, thermal expansion of the conductivity cell prior to 1m bin averaging and derived parameters (e.g. Salinity PSS-78).

Water Sampling and Analysis

On the same cast for the CTD, Niskins bottles were attached at various depths (see Table 2-7 and Figure 2-17). These depths were based upon standardised oceanographic sampling depths, and optimised with respect to the 50m and 100m CSIRO Port Hacking water quality stations. Annual thermocline activity observed from the Ocean Reference Station (situated 4 km off Bondi in 60m of water) was also taken into consideration along

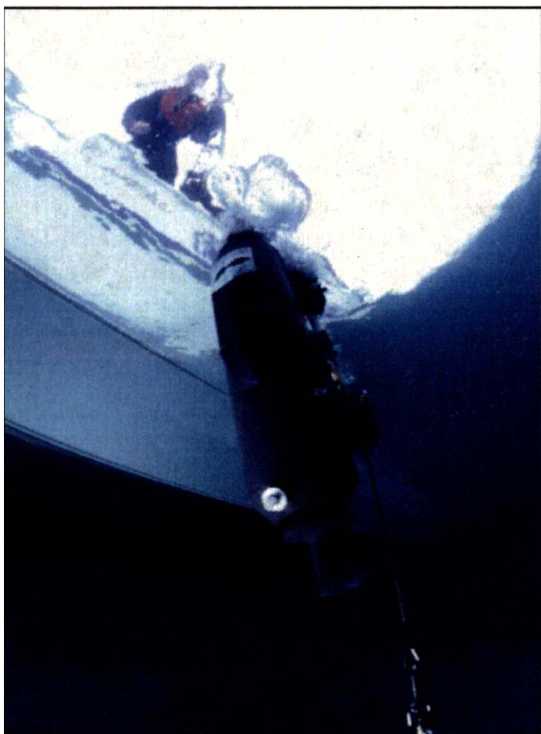


Figure 2-17: Firing Niskin bottle captures a sub-surface sample.

with logistical capabilities before the sampling depths were finalised. For each cast, the CTD logged bottom depths were compared to cast depths (from the marked cable) to assist with determining actual depths of Niskin bottles. From each Niskin bottle water samples were collected for nutrient and chlorophyll-a analysis as well as for algal counts.

After each CTD cast, a weighted 20 μ m mesh plankton net was deployed on station and hauled vertically to capture an integrated sample of phytoplankton in the surface mixed layer (0-50m haul) for qualitative algal identifications (see Figure 2-18).



Figure 2-18: The 20 micron algal net used during the routine transects off Port Hacking, Port Stephens and Jervis Bay.

Immediately after collection water samples were decanted into the following bottles from each Niskin:

- a 500 ml polystyrene bottle - nutrient analyses
- a 2.2 litre amber bottle - chlorophyll-a analysis
- a 250 ml bottle - algal identification and cell count

(Note: All bottles were rinsed with the sample prior to filling. Once filled, all sample bottles were capped and placed in an esky.)

In the laboratory, dissolved nutrient samples were filtered using 0.2 µm “Mini-sart” disposable filters. For low silica analysis a 10 ml vial was filled with the filtrate and for low free reactive phosphorus, low ammonia nitrogen and low NO_x-N one 30 ml vial was filled. The 10 ml vials were stored in the dark at room temperature and the 30 ml vials were stored frozen at -20 °C. The chlorophyll-a filtrate was collected from the water sample on a Whatman 0.7 µm glass fibre filter using a vacuum filtering system. These filter papers were then wrapped in foil, labelled and stored frozen at -20°C until chlorophyll-a determination was undertaken by the NSW EPA laboratories. The methods used for nutrient and chlorophyll analysis with detection limits are given below in Table 2-8.

Table 2-8: Nutrient auto-analysis and chlorophyll-a techniques and detection limits.

Test ID	Methods used during testing	Practical Quantitation Limit (µg/l)
Low ammonia nitrogen	*APHA Method 4500 - NH ₃ H	2
Low free reactive P	*APHA Method 4500 - P G	1
Low NO _x - N	*APHA Method 4500 - NO ₃ I (Modified)	1
Low Silica (SiO ₂)	*APHA Method 4500 - Si F (Modified)	5
Chlorophyll-a	*APHA Method 10200	<1

* From Standard methods of water and wastewater analysis, American Public Health Association publication, 20th edition, 30M12/98

Algal Identification/Counts

Algal samples were preserved immediately after collection with 3% glutaraldehyde and refrigerated until further investigation. Vertical net haul samples from each station were for general examination - taxa presence/absence (overall taxa list). Other samples taken at various depths were only examined when their corresponding (depth) chlorophyll-*a* concentrations are $>1 \mu\text{g/L}$. All algae (dominant and subdominant) were noted and cell counts for each taxa was carried out.

Quality Control/Quality Assurance

The field and laboratory QA/QC program included field blanks for nutrients and random duplicates for chlorophyll-*a* analysis. Laboratory calibration of chlorophyll-*a* and salinity was done routinely for each cast on each transect run. Factory CTD calibrations were done at the start and end of the sampling season by the manufacturers in the USA (Seabird Electronics), and routine stability checks prior to each field trip to maintain the quoted accuracy of the sensors. The accuracy of current measurements from the ADCP is dependant on the acoustic stability of its 300 KHz signal, and associated internal processing. This stability was routinely tested in the laboratory via a series of testing procedures recommended in the manufacturer's manual.

2-3-2 Routine transect sampling in New Zealand

This field program was part of the *NOEX (Nearshore/Offshore EXchange)* study conducted by the National Institute of Water and Atmospheric Research, New Zealand (NIWA). NOEX was a 3-year field and numerical modelling investigation (1994-96) being conducted by NIWA off the east-coast of the North Island to examine the exchange of sediments and nutrients along and across the continental shelf.

The interest in the shelf waters off the east coast of northern New Zealand with respect to the Australian study, is the connection by the prevailing Western Boundary Current in the South Pacific, respectively known as the East Australian Current (EAC) and the East Auckland Current (EAC-NZ).

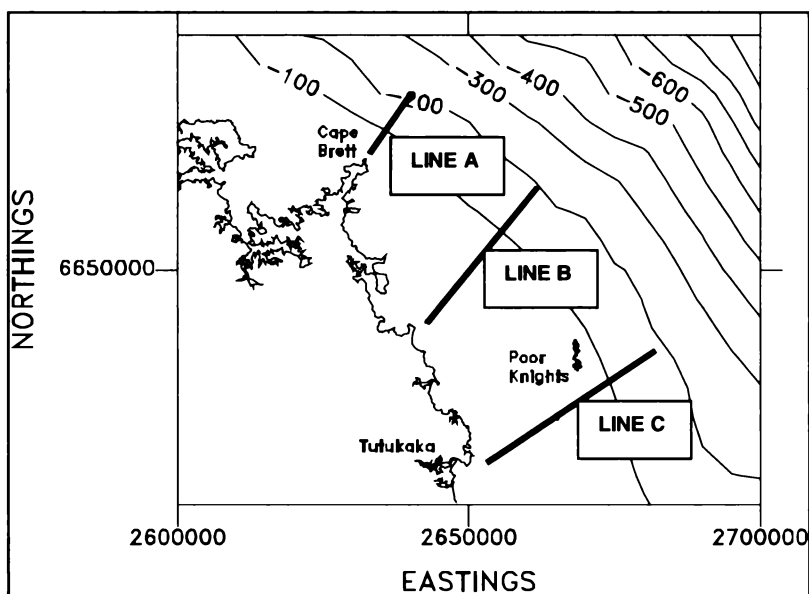
Strong shelf interaction of this geostrophic flow in both regions is often associated with shelf slope intrusions of nutrient rich water (Cresswell et al, 1983; Godfrey et al, 1980; Tranter et al, 1986; Stanton 1979; Denham et al, 1984; Stanton et al, 1996). The intensity of these interactions have also been shown to be affected by ENSO with ramifications on phytoplankton populations (Harris et al, 1987; Ballantine, 1995; Rhodes et al, 1993; Taylor et al, 1985).

The investigations of the NOEX program in New Zealand were concurrent with studies on the New South Wales coast and similarly designed to capture the physico-chemical and phytoplankton characteristics of shelf waters responding to coastal upwellings. Although the inclusion of their results has been confined to the discussion (Chapter 8), it is considered appropriate to outline their logistics in this section to provide a comparison to the Australian studies.

Site Selection

The north east coast of New Zealand was chosen due to its proximity to the free flowing Auckland current and a relatively similar shelf profile to the NSW coast, in an attempt to compare with EAC shelf impacts on the NSW coast. After splitting off from the EAC (~50% of the flow) and heading east along the Tasman front, this section of the South Pacific's western boundary current intensifies on the east coast of New Zealand's North Island and flows southward (see Figure 1-6) as the EAC-NZ. The section of coast north of the Poor Knights Island group was selected as it was clear (to the north) of islands, had a relatively straight coastline paralleled by the bathymetry and forms the upstream boundary of the Hauraki Gulf where phytoplankton blooms have been of interest. This region was therefore expected to be influenced by a relatively uninterrupted stream of the EAC-NZ. The three transects shown in Figure 2-19 were sampled a total of 14 times between 1993-1995 for the NOEX program (Sharples et al, 1995). Data from these cruises was provided by NIWA to complement subsequent transects made during this study.

Figure 2-19:
Locations of the
Cape Brett (Line A),
Rimariki Island
(Line B), and Cape
Rodney (Line C)
transects taken off
New Zealand
between 1993 and
1997 as part of the
NO-EX program.



Two transects

that correlate with lines A and B from the NOEX cruises (Sharples et al 1995), were adopted for further transect work as they were in a region considered most likely to experience shelf influences of the EAC-NZ. The section through Cape Brett is across the steepest and narrowest part of the shelf while the Rimariki transect is in the lee of Cape Brett, is wider, and forms the upstream boundary to the Hauraki Gulf. During 1995 and 1996 four surveys were made along these two transect lines with station sampling intervals and depths based upon the transects off the NSW coast (Figure 2-14).

The locality map in Figure 2-19 indicates the offshore tangent of the shelf break (relative to the coast) between lines A and B would promote topographic steering of the Auckland current and therefore provide potential for an uplifting/upwelling of slope waters onto the shelf. Recent NOEX data in Sharples (1996) and Sharples et al (1995) frequently confirms the occurrence of this scenario. The Cape Brett Transect was 12 kms long and consisted of seven instrumental profiling stations. Profile details are given in Table 2-9. The hydrographic data was collected along NOEX line A primarily to assist as an upstream boundary condition for the NOEX modelling component.

Table 2-9: Cape Brett Transect (NOEX Line A) & Rimariki Island Transect (NOEX Line B).

Cape Brett Transect (NOEX line A)				
Site Code	Latitude	Longitude	Station Depth (m)	Distance Offshore (km)
A1	35° 9.9'S	174° 20.4'E	50	0
A2	35° 9.2'S	174° 20.74'E	110	1
A3	35° 8.8'S	174° 21.09'E	115	2
A4	35° 8.3'S	174° 21.46'E	130	3
A5	35° 6.9'S	174° 22.6'E	140	6
A6	35° 5.6'S	174° 23.84'E	170	9
A7	35° 4.4'S	174° 25'E	205	12
Rimariki Island Transect (NOEX Line B)				
B1 - 20	35° 25.4'S	174° 27.1'E	0,5,10	0
B2 - 50	35° 25'S	174° 27.5'E	0, 5, 20, 40	1
B3 - 60	35° 24.74'S	174° 28.03'E	0, 5, 20, 50	2
B4 - 70	35° 24.27'S	174° 29'E	0, 5, 20, 50, 60	3
B5 - 80	35° 23.5'S	174° 29.33'E	0, 5, 20, 50, 70	5
B6 - 115	35° 21.5'S	174° 31.7'E	0, 5, 20, 50, 100	10
B7 - 140	35° 18.5'S	174° 35'E	0, 5, 20, 50, 100, 120	17.5
B8 - 160	35° 15.34'S	174° 38.03'E	0, 5, 20, 50, 100, 150	25
B9 - 210	35° 12.8'S	174° 39.4'E	0, 5, 20, 50, 100, 150, 200	30

It has, however, proven to be a useful guide (in the absence of current metering) to indicate the degree of crossshelf circulation with respect to measurements made some 25 km downstream along line B. The transect line taken out from Rimariki Island was 30 km in length and similar in profile to shelf shapes on the NSW coast. Nine profiling stations, as

detailed in Table 2-9, included water sampling as well as the collection of electronic measurements.

Instrumentation/Resources

The Earth Sciences Department at the University of Waikato has supported the project with financial, technical and field assistance during the 1995/96 sampling season. Their DGPS equipped 9 m Survey vessel *Tai Rangahau* was employed during the study under the technical supervision of Dirk Imenga from the Earth Science Department.

Logistical coordination of the field exercises was initially set-up by Randall Lee whilst at NIWA in August 1995, and then coordinated through technicians Penny Spong and Andrew Sayce. Four sampling excursions undertaken during the 1995/96 spring/summer season occurred on 2 August 1995, 7 October 1995, 17 November 1995 and 16 January 1996.

NIWA Hamilton's Applied Microsystems Salinity, Temperature and Depth profiler STD-12, (SN 461) was employed for the majority of the cruises. The basic remotely operated STD-12 runs at 8Hz and provides resolution (accuracy) of temperature at 0.001°C (0.01°C), salinity at 0.005 ppt(0.01 ppt) and calculated sigma- t to 0.001kg/m³ (0.05 kg/m³). The STD-12 was sent back for calibration after the first cruise, and a Chelsea Instruments Aquatracker CTD was provided by NIWA Wellington. This instrument has comparable performance and had a Fluorometer (built into the CTD pack. It also was the instrument used during the 1993-1995 NOEX cruises by Sharples et al (1995).

Water Sampling and Analysis

On the Rimariki Island transect and in conjunction with STD-12 deployments, Niskin/Nansen bottles were attached at various depths (see Table 2-9). These depths were based upon standardised oceanographic sampling depths adopted for the Australian studies, modified with respect to the thermocline structure seen from long-term NOEX deployments, and optimised after consideration of actual cruise time. From each Niskin/Nansen bottle, water samples were collected for nutrient and

chlorophyll-*a* analysis. Immediately after collection, water samples were decanted into the following bottles from each Niskin.

- triplicate 250- 500 ml polystyrene bottle for nutrient analyses
- 1-2 litre amber bottle for chlorophyll-*a* analysis

All bottles were rinsed with the sample prior to filling. Once filled, all sample bottles were capped and placed in a portable cooler. During each STD-12 cast, a vertical plankton 20 µm net haul from 50 m to the surface is to be made to represent cumulative algal activity in the eutrophic zone. Upon returning to the laboratory, nutrient samples are filtered using 0.2µm “Mini-sart” disposable filters. For low silica analysis, a 10 ml vial is filled with the filtrate. For low free reactive phosphorus, low ammonia nitrogen and low NO_x-N one 30 ml vial is filled. The 10 ml vials are stored in the dark at room temperature and the 30 ml vials are stored frozen at -20 °C. In the laboratory, the chlorophyll-*a* sample was collected from the water sample on a glass fibre filter using a vacuum filtering system. These filter papers were placed in purpose built plastic bags, labelled and stored frozen at -20 °C until chlorophyll-*a* determination began.

In March 1996 the entire suite of samples for the 1995/96 season were shipped frozen to the NSW EPA laboratories in Sydney, Australia for auto-analysis. The samples arrived intact and frozen, and were placed in laboratory freezers until analysis. Sensitivity tests were initially run on the NSW EPA's Lachat autoanalyser prior to sample analysis. The methods used for nutrient analysis and their detection limits are the same as employed in the Australian studies and are given in Table 2-8.

Algal Identification/Counts

Algal samples were preserved immediately after collection with 3% glutaraldehyde and refrigerated until further investigation. Vertical net haul samples from each station provided a general examination of planktonic activity in the eutrophic zone by assessing species presence/absence (overall species list), subdominant and dominant species.

Quality Control/Quality Assurance

The field and laboratory QA/QC program will include field blanks for nutrients and random duplicates for both nutrients and chlorophyll-*a* analysis. Laboratory calibration for salinity is done routinely with surface and bottom samples collected from each cast on each transect run. An annual factory calibration is done on the STD-12 by the manufacturers in the USA. Temperature stability of the STD-12 is routinely tested prior to a cruise with a high-resolution thermometer in a temperature bath.

2-3-3 Sampling Timetables

The sampling timetable for the respective programs in Australia and New Zealand are provided in Table 2-10. NOEX sampling during six cruises from December 1993 to January 1995 undertaken and analysed by NIWA have been combined with the four 1995/96 cruises to improve characterisation of nutrient-temperature relations.

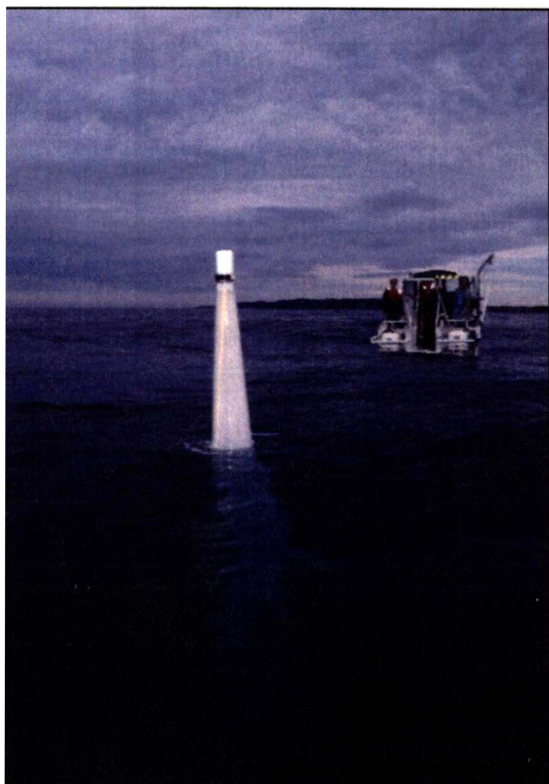
Table 2-10. Sampling timetable for the ocean nutrient and phytoplankton project 1995-1998 in Australia and NIWA's C-SEX program in New Zealand 1993-97.

LOCATION	Dec - Aug 93/94	Oct-Mar 94/95	Oct-Mar 95/96	Oct-Mar 96/97	Oct-Mar 97/98
Port Stephens Australia	NA	NA	3	1 routine 4 responsive	NA
Port Hacking Australia	NA	NA	5	1 routine	8 responsive 51 (0-10km)
Jervis Bay Australia	NA	NA	3	1 routine 6 responsive	1
Cape Brett New Zealand	3	2	4	NA	NA
Rimariiki Island New Zealand	2	2	4	4	NA
Cape Rodney New Zealand	3	2	NA	NA	NA

2-4 PHYTOPLANKTON RESPONSES

2-4-1 12-month study

A 12-month weekly sampling program commenced in April 1997 in a manner consistent with monitoring undertaken by Hallegraeff (1981). Both studies focussed on quantitative phytoplankton and companion hydrographic sampling at the CSIRO Port Hacking long-term monitoring station (PH100), looking at abundances, distributions and successions of phytoplankton taxa.



A quantitative 20µm sampling net (see Figure 2-20), identical to the unit used by Hallegraeff (1981), was used to collect a cumulative sample between the 0-50m depth representing the euphotic zone.

The work was also accompanied by sampling for larger dinoflagellates and zooplankton using nets with a larger 100µm mesh size.

Figure 2-20 A quantitative 20µm sampling net, identical to the unit used by Hallegraeff (1981) deployed off EPA vessel RV Aquilla

Supporting the biological information was physio-chemical data collected by Seabird SBE25 CTD and 5-litre Niskin water sampling (at depths similar to CSIRO station sampling - see section 2-4.1) at both the PH100 site and the longterm Port Hacking site in 50m (PH50) at depths (see Figure 2-21). CTD profiling was extended both inshore and offshore of the PH50 & PH100 sites to form a 10km transect across the inner and mid-shelf zones.

This allowed shelf dynamics to be examined in conjunction with the biological activity. Water sampling included ammonia, chlorophyll-a and algal count analysis to the standard suite of nutrients routinely sampled at PH50 and PH100 by the CSIRO.

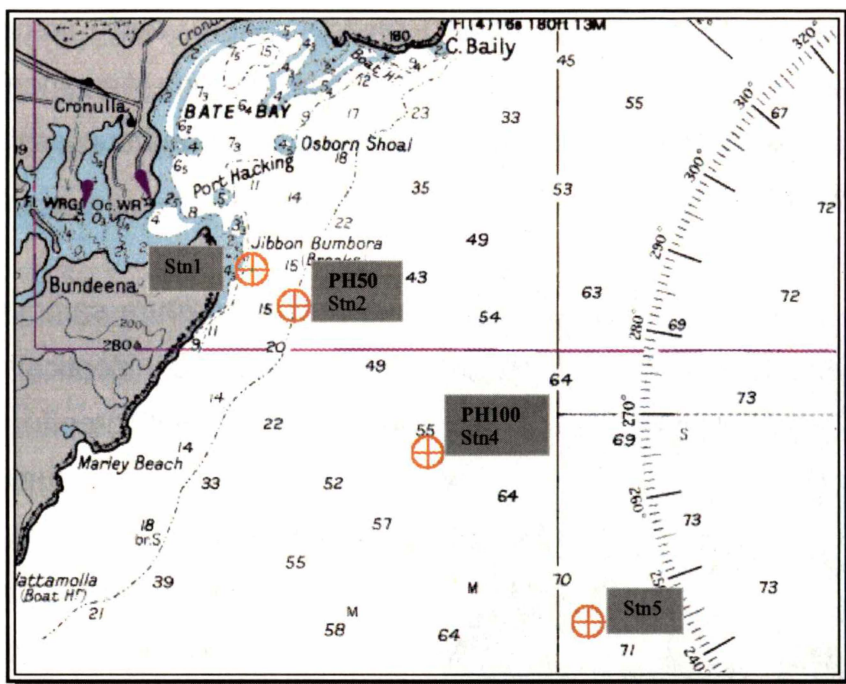


Figure 2-21: Long-term sampling stations off Port Hacking in 50m (PH50) and 100m (PH100), as used during the twelve month study April 1997-98.

2-4-2 Responsive Sampling

Based on the routine transect sampling design and sample processing (see 2-2-1), responsive short term time series sampling transects were undertaken during upwelling events that occurred within the study region from Port Stephens to Jervis Bay during the program. Responsive sampling attempted to quantify the relative changes in nutrient concentration and algal mass during a bloom cycle with respect to the ambient oceanographic conditions. Repeated transect lines in the vicinity of the upwelling/uplifting, aimed at capturing these changes during an event. A transect was repeated, weather and time permitting, for a period of 1-2 months until ambient conditions returned. Regular monitoring of NOAA SST images and the ORS, provided the tools for determining coastal upwellings in the study region. The responsive sampling program

was triggered for the Jervis Bay (JB) and Port Stephens (PS) transects in January-March 1997, and at the Port Hacking (PH) transect in January 1998.

2-5 LONG-TERM PATTERNS

2-5-1 Port Hacking Long-term records

Weekly to monthly sampling runs at Port Hacking, Sydney, have been in operation since 1942 by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) collecting temperature, salinity and nutrients through the water column at two stations, PH50 and PH100, located in 63m and 105m of water respectively (see Figure 2-20). The PH50 station was sampled at 0, 10, 20, 30, 40 and 50m depths, and at the PH100 station samples were taken at 0, 10, 25, 50, 75 and 100m depths. Free Reactive Phosphorous (FRP), Oxidised Nitrogen (NO_x-N) and silica were the predominant nutrients sampled for analysis. Sampling depths at the PH100 site frequently changed (between some 16 different depth formats), rendering 0, 10, 50 and 100m as the only consistently sampled depths for a comparative time series. As the PH50 station has a better data coverage over depth and has a comparable depth to the ORS, less focus is placed on the PH100 record. Within the timeframe of these records, a number of analytical procedures changed for nutrient analysis rendering some periods in the data-set incompatible. Sample results prior to 1957 (and in the case of PH100, 1953) for FRP, and values prior to 1965 for NO_x-N have been removed as the respective FRP and NO_x-N analysis were inconsistent with subsequent results. Silica analysis commenced late in the records in 1968 with a number of manual methods of varying accuracy utilised until 1972 (Airey and Storey, 1987). Between 1971 and 1984 a more accurate manual technique was adopted, and in 1984 all analysis became automated. The variable results prior to 1971, however, have been removed from our analysis.

Airey and Sandars (1987) provided comparisons of automated nutrient analysis to the previously employed manual techniques by CSIRO

laboratories, and found that only for FRP were the two methods equivalent within the precision of the procedures for sampling, storage and analysis. Airey and Storey (1987) indicate that a ~10% adjustment would be required to compensate overestimated NO_x-N results from the analytical technique employed between 1975 and June 1984. For silica, a positive offset became apparent in the records when automated methods were introduced. Airey and Storey (1987) indicate that automated and manual comparisons from like regions, sampling depths and seasons, would provide an indication of the offset. Using this approach the offset for the Port Hacking data averaged ~30ug/L. The 10% adjustment for NO_x-N, and the 30ug/L silica offset, has been applied for our analysis of the PH50 & PH100 data.

2-5-2 Meteorological data

As two of the controlling factors for algal bloom activity, data for daily rainfall and sunshine hours were obtained from the Australian Bureau of Meteorology for the duration of the program. Data from Williamstown (*Station # 61078*), Sydney Airport (*Station # 66037*) and Nowra Air Station (*Station # 68076*) were used to represent respective local conditions off Port Stephens, Port Hacking and Jervis Bay. The Southern Oscillation Index (SOI) was used as an indicator of long-term climatic variation, This index is based on the pressure differential between Darwin and Tahiti to indicate ocean dynamics across the western Pacific, and is a common method for indicating the strength of the El Niño Southern Oscillation. Data was obtained as monthly SOI's dating back to 1876 through the Australian Bureau of Meteorology's web site (www.bom.gov.au).

Chapter 3: Anthropogenic sources

3-1 CONTEXT OF PAPERS WITHIN THE THESIS

To address the issue of anthropogenic inputs to the coastal ocean, a range of potential sources were considered and initially reviewed in the literature. These sources included point discharges of sewage, industrial pollutants, stormwater discharge, estuaries, and diffuse sources from atmospheric fallout and sediment re-suspension. Considering the scope of the thesis, and the ONPP (on which it was based), not all sources were able to have a thorough examination throughout the project. So the initial review, provided in the first paper, aimed at identifying the major contributors specifically influencing the study region off NSW coast, which were potentially quantifiable as a load. These comparisons found that the most significant contributions in the study region were likely to be from sewage and estuarine discharges. These point sources could be quantified respectively through license monitoring within the sewage treatment plants and a gauge network for flood monitoring. The results from the two papers representing this chapter explore these major anthropogenic nutrient sources in the study region. The distribution of the major discharges in the region are identified, quantified, and their discharges and dispersion characterised. Whilst sewage discharges are typically continuous, estuarine sources express their input in a more episodic nature, thus requiring event frequency and durations also to be considered. The content of the second paper addresses such an episode experienced during the study program and attempts to quantify its effect on adjacent ocean waters. The comparisons of these major sources to all sources are considered further within the overview and discussion chapters.

The first paper in this chapter was published in the Journal of Coastal research in 2001, as the following reference.

Pritchard, T.R., Lee, R.S., (2001). How do ocean outfalls affect nutrient patterns in coastal waters of New South Wales, Australia?, Journal Coastal Res., 34, p. 87-95.

The second paper in this chapter was published as a peer reviewed manuscript in the Proceedings of the Coasts and Ports conference 1999, as the following reference.

Lee, R.S., and Pritchard, T. R., (1999). Extreme discharges into the coastal ocean: A case study of August 1998 flooding on the Hawkesbury and Hunter Rivers. 14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports 1999.

3-2 HOW DO OCEAN OUTFALLS AFFECT NUTRIENT PATTERNS IN COASTAL WATERS OF NEW SOUTH WALES, AUSTRALIA?

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Running Head: Ocean outfall nutrient patterns

Abstract

This study investigated the effects of major sewage and estuarine discharges on nutrient distributions in the central New South Wales (NSW) coastal waters. The hinterland of the study region includes the sewerage and rainwater catchments of major population centres of Newcastle, Sydney and Wollongong. New South Wales discharges the majority of its treated sewage to the ocean, with about 80% from just three deepwater outfalls off Sydney. These discharges were found to be the principal, continuous, anthropogenic source of nutrients to NSW coastal waters. The deepwater outfalls delivered most of their nitrogen as ammonia and were responsible for nutrient ($\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$) enrichment within usually submerged effluent plumes. Direct observations and modelling indicate that after initial dilution, effluent plumes typically occupy ~30m of the water column (60-80m). Rapid initial dilution was observed with subsequent gradual far field dispersion typically broadening the effluent field to 1-2 kilometres by about 10 kilometres downstream. Flows generally follow isobaths, predominantly to the south. Vertical and seasonal distributions of sewage derived nutrients, were estimated from a 6 year record of initial dilution modelling and effluent data. Comparisons were made with ambient nutrient distributions derived from long term monitoring prior to the commissioning of the outfalls (1990), at the CSIRO Port Hacking Station (5 to 10 kilometres south of the deepwater outfalls). The pycnocline seasonally limited the vertical extent of sewage plumes emitted from the deepwater outfalls. Upwelling/uplifting processes were associated with stratified conditions during spring and summer. Therefore, density stratification was a critical factor in determining the vertical movement of oceanic and sewage derived nutrients into the euphotic zone. Despite clear nutrient enrichment due to sewage discharges, no new evidence has been presented to contradict previous findings that algal blooms are principally driven by oceanic nutrient enrichment. However, by considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns we have identified specific periods of the year and depth intervals with maximum risk of outfall impacts, such as the upper half of the water column during late summer.

Index Words: New South Wales, sewage outfalls, nutrients, algal blooms.

Introduction

New South Wales' (NSW) population is concentrated along the coast and in particular in Sydney, Newcastle, Wollongong and adjacent areas. Most of the sewage generated in the coastal zone of NSW is discharged to the ocean after being treated to varying degrees. High levels of nutrients are found in sewage effluent regardless of the standard of treatment.

In NSW coastal waters, there have been concerns that the periodic occurrence of marine algal blooms, particularly 'red tides' of the dinoflagellate *Noctiluca scintillans* (Hallegraeff, 1993), may be related to major anthropogenic nutrient loadings such as those from sewerage treatment plants.

Eutrophication has been recognised as a serious threat to the health of coastal ecosystems both in Australia (e.g. Zann, 1995) and globally (e.g. Pelley, 1998). Furthermore, some evidence exists for a worldwide increase in the occurrence of harmful blooms (Anderson 1985), Paerl, H., 1997). Anthropogenic discharges such as from sewage treatment plants have been identified as a possible factor in the increased eutrophication of some coastal waters (Smayda 1990, 1997). And, some laboratory studies have shown that sewage effluent enrichment (dilution range 1:200 to 1:5) can increase the populations of 'nuisance' and potentially harmful phytoplankton at the expense of naturally occurring benign diatoms as well as increasing overall phytoplankton production (Pan & Subba Rao, 1997).

The purpose of this paper was to investigate the contributions to coastal waters of nutrients from major sewage ocean outfalls. In order to achieve this we attempted to determine ambient (non outfall) nutrient distributions and patterns, quantify nutrient enrichment patterns due to major outfall sources and, discuss the importance of outfall nutrients in relation to phytoplankton activity.

Study Region

Our study focused on the waters of the continental shelf between Port Stephens and Jervis Bay (Figure 1). In this region the continental shelf (to 200m isobath) is relatively narrow, ranging from about 45 kilometres in the north to about 20 kilometres off Jervis Bay in the south. The hinterland of this region includes the sewerage and rainwater catchments of the major population centres of Newcastle, Sydney and Wollongong. At least twenty outfalls discharge sewage effluent directly to the ocean in this region.

Particular emphasis was given to the Sydney coastal waters which receive the vast majority of sewage effluent mainly via three deepwater ocean outfalls off North Head, Bondi and Malabar. These outfalls were commissioned between September 1990 and August 1991 to replace cliff face outfalls. The study region lies in a transitional zone.

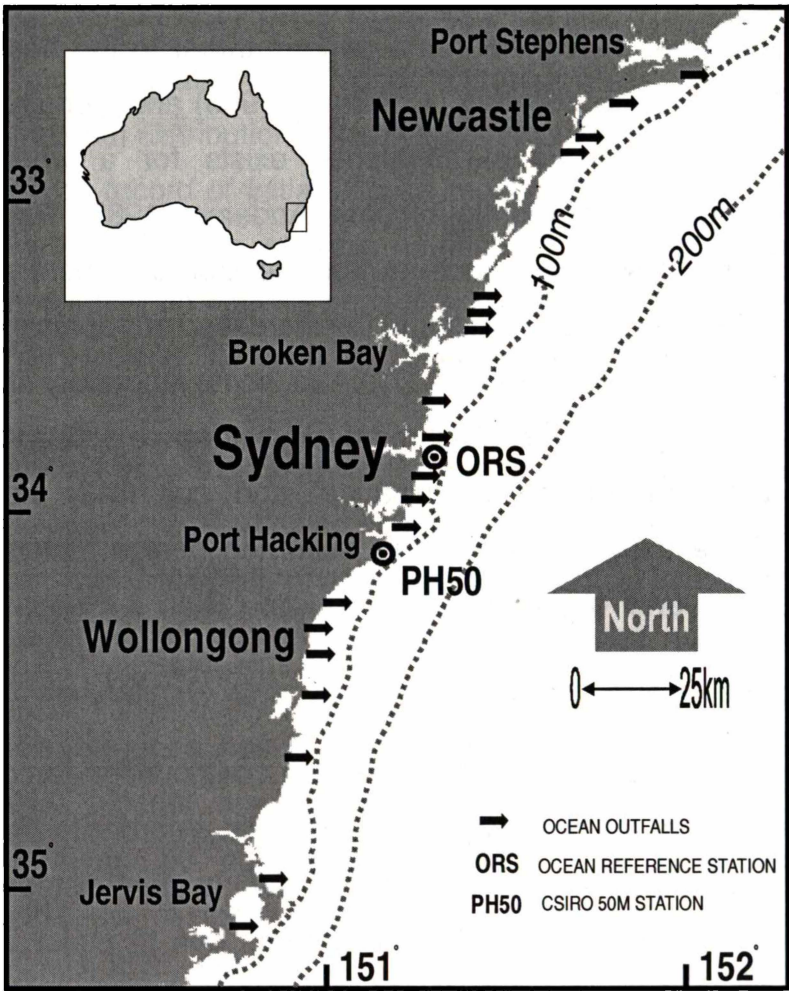


Figure 1. Study location showing ocean outfalls and locations of principal data sources.

From the north the warm, oligotrophic waters of the East Australian Current (EAC) carry plankton of tropical origin. The main EAC flow typically separates from the NSW coast and flows eastward just north of the

study region. Instability along the front between the warm EAC water and

the colder Tasman Sea water often leads to the formation of both large (~150km) warm core anticyclonic eddies and smaller (20-50km) cold core cyclonic eddies which may persist for days to many weeks (Cresswell and Legeckis, 1986). Ekman pumping can lead to the uplifting of nutrient rich bottom waters shoreward across the shelf when southward EAC flows impinge on the shelf and can also lead to more localised uplifting/upwelling at the centre of cold core eddies (Oke, 1997). Local changes in coastal bathymetry/orientation appear to pre-dispose certain locations, such as areas Port Stephens to Newcastle, Port Hacking to Wollongong and Jervis Bay, to EAC induced nutrient rich slope water intrusions (Lee *et al.*, 2001).

Other dynamic processes controlling the introduction and dispersion of oceanic and anthropogenic nutrients in the study region include local winds (Griffin and Middleton, 1991), northward propagating coastal trapped waves (CTWs) (Church *et al.*, 1986; Griffin and Middleton, 1991), relatively high frequency internal waves and tides (Griffin and Middleton, 1992) and swell waves. Local winds operate over distances of 10 to 100 km and periods of hours to a few days: south-easterly winds favour downwelling while upwelling favourable north-easterly winds have been shown to be critical in pre-conditioning for upwelling (Oke, 1997).

Vertical mixing of nutrients is critical to light limited phytoplankton populations. Offshore waters remain stratified for most of the time with temperature stratification of up to nearly 10°C reported by Wilson *et al.* (1995). Some vertical mixing may occur across the thermocline due to current shear but significant stratification generally persists unless either an oceanic water mass moves in to swamp shelfwaters or a vigorous mixing process erodes the thermocline. De-stratification of the entire water column has been observed over periods of less than 24 hrs under the influence of strong winds and waves (Lee and Pritchard, 1996). Internal waves may also contribute to vertical mixing if they shoal and break on the inner shelf.

For further details, Lee and Pritchard (1996) illustrate the significance of these various oceanographic processes in relation to the dispersion of effluent from Sydney's deepwater outfalls.

Methods and Data Assessment

In addressing our objectives we analysed data and information from a range of sources. Various catchment and effluent monitoring data were accessed to indicate the relative importance of various non-oceanic nutrient loadings to coastal waters although sparse or inappropriate data coverage limited the extent to which load data could be analysed. Nutrient exports from coastal catchments were based on various observed and modelled estimates for 11 major catchments from the Hunter (Newcastle) in the north to Jervis Bay in the south as described by SKM (1997). Flow data were generally well represented but temporal and spatial coverages of nutrient concentration data were variable (especially for smaller catchments) limiting some quantitative assessments.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has collected mainly physico-chemical data offshore from Port Hacking (PH) since the 1940's (Humphrey, 1963). Ambient nutrient concentrations were obtained for the surface and at 10 m depth intervals to 50 m at CSIRO PH50 (34° 05'S., 151°13E.) in water depths of 50-60 m. Data were limited to those from periods of more consistent chemical analyses prior to the commissioning of Sydney's first deepwater outfalls: nitrate ($\text{NO}_3\text{-N}$) from 1965 to September 1990 and phosphate ($\text{PO}_4\text{-P}$) from 1957 to September 1990. Prior to 1990, similar quantities of effluent were discharged via shoreline outfalls resulting in surface plumes but extensive monitoring prior to the commissioning of deepwater outfalls suggested little or no impact at PH50 (Pritchard *et al.*, 1996) Analytical methods have been described elsewhere by Lee *et al* (2000-this volume), Major *et al* (1972), Airey and Sanders (1987). Sampling frequencies varied from approximately weekly ($\sim 47 \text{ year}^{-1}$) before 1985 to about monthly ($\sim 10 \text{ year}^{-1}$) after 1985. The change in sampling frequency was not expected to bias nutrient distributions with respect to variability associated

with El Niño Southern Oscillation (see Lee et al, 2000 – this volume) because the period of reduced sampling included similar periods of cold (La Niña) and warm (El Niño) (NOAA, 2000). For the purpose of contouring, CSIRO PH50 data were grouped by month of the year and depth before percentiles were calculated (i.e. Figure 4).

Sydney Water's Ocean Reference Station (ORS) located 3 to 4 kilometres off Bondi in 64m of water, provided near continuous current measurements at 17 m and 52 m depths (Interocean S4 current meter accuracy 0.01 m/s) and temperatures throughout the upper 52 m of the water column. Sydney Water continuously monitors Sewage Treatment Plant (STP) flows while Sydney Water effluent nutrient concentrations were obtained from focused sampling during 1993/94 and 1996/97 (Sydney Water, 1997; Hunter Water Corporation, 1998; MHL, 1997). Organic nitrogen was calculated as the difference between total Kjeldahl nitrogen (TKN), and ammonia-N (plus nitrate). Its splitting into dissolved and particulate organic nitrogen was done on the basis of unpublished concentration data collected by Sydney Water in 1993/94.

For Sydney's deepwater outfalls, the near-field model JETLAG (Lee and Cheung, 1990) was used, together with ORS and STP data to estimate initial effluent dilution, plume thickness, and plume centre line depth. The formulation of JETLAG tracks the evolution of the average properties of plume elements at various time steps by conservation of horizontal and vertical momentum, conservation of mass accounting for entrainment, and conservation of tracer mass. Sensitivity testing and comparisons with data obtained from plume tracing experiments conducted off Malabar indicated that JETLAG provided a good representation of plume behaviour (Cathers and Peirson, 1991). JETLAG was therefore used to compile a time series to represent plume characteristics immediately after initial momentum and buoyancy driven dilution.

Hourly average JETLAG model results were obtained for periods when both STP and ORS data were available during the period from January

1991 to December 1998 (54856 records or 78% coverage). When compared to cold and warm episodes (NOAA, 2000), modelled coverage was equivalent to a ~17% bias to El Niño conditions. That is, when a simple scoring system was employed, the modelled period included an excess of El Niño conditions equivalent of nearly 400 (of 2290) days of moderate El Niño conditions.

The water column was divided into 2m depth bins in order to represent the effluent contribution to the water column after initial dilution. For each model run, the average initial dilution was assigned to those depth bins spanned by the vertical extent of the plume and a null result was assigned to bins which fell outside the plume. Depth bins were then grouped by month of the year and 10m depth intervals in order to estimate frequency of occurrence of effluent (percent effluent present – as in Figure 7) and percentile effluent concentrations (1/dilution) over a 12 months x 5 depths grid. Nutrient contributions were then calculated for each grid element (and each percentile effluent concentration) based on fixed average nutrient concentrations observed in primary treated effluent (Tables 1 & 2) and percentile ambient nutrient concentrations observed during long term monitoring at PH50 (Figures 8 and 9). In addition, all near-field model results for each outfall were allocated to 2m depth bins irrespective of month of the year and results were grouped by 10m depth intervals. Percentile effluent dilutions were then estimated for each 10m depth interval (i.e. 5 x 2m bins) by including only results for when effluent was present. In this way, it was possible to estimate initial effluent dilutions with respect to plume depth (as in Figure 6).

Effluent plume behaviour was illuminated using data drawn from various near-field model verification experiments conducted using a SEABIRD SBE25 Sealogger (temperature accuracy 0.004°C and conductivity 0.0003 S/m) and radioisotope tracer (introduced Tritium, Gold-198 and Technetium-99m isotopes) techniques similar to those described by Pritchard *et al.* (1993). Radioisotope studies were conducted in

collaboration with Australian Nuclear Science and Technology Organisation.

Nutrient Sources

In nutrient limited systems, algal responses are driven by the concentration of nutrients in the water column while the overall algal biomass (extent and longevity of blooms) is also a function of the nutrient load entering the system. Therefore, both the concentrations and loads of nutrients are important when considering nutrient sources.

Nutrients enter the study region from discrete point sources such as ocean outfalls and estuaries (coastal catchments), from diffuse atmospheric and sediment sources at the upper and lower boundaries of the system and from oceanic sources such as the cross shelf nutrient fluxes associated with slope water intrusions (Pritchard *et al.*, 1999). Various bio/geo-chemical processes act to exchange and transform these nutrients within the system. Nutrient concentration data (Table 1) for ambient ocean waters and key sources of nutrients to coastal waters indicate the potential for enrichment of surface waters due to estuarine discharges (especially nitrate and ammonia) and outfalls (especially ammonia) on those occasions when sewage effluent plumes surface. Bottom waters may be enriched by slope water intrusions (especially nitrate and phosphate) and by outfalls (especially ammonia). There is also a potential for vertical transport (upwelling or mixing) to dramatically enrich surface waters.

Table 1 Indicative Nutrient Concentrations

	Nitrate NO ₃ -N (ug/L)	Ammonia NH ₄ -N (ug/L)	Phosphate PO ₄ -P (ug/L)
Reference ¹	10-60	<5	1-10 ¹
Primary Effluent ²	30	23,000 – 28,000	3,200 – 6,400
Run-off ³	110 – 450 ^{NOx}	50 - 360	40 - 90
Ambient shelf Upper waters ⁴	10	8*	7
Ambient shelf Lower waters ⁴	70	8*	15
Slope Waters ⁵	> ~ 140	~ 6-8 [#]	22

Sources: 1 ANZECC (1992); 2 Range of geometric means for Sydney Water's Sewage Treatment Plants at North Head, Bondi and Malabar 1994-95 (no dilution); 3 Range of 90 percentile values across a variety of catchment types based on 1993 & 1994 data from the Sydney Water Corporation's Stormwater Monitoring Program (from Sinclair Knight Merz, 1997). Values relate to stormwater entering the estuarine system which may or may not be representative of estuarine discharges to the ocean; 4 Median concentrations observed at CSIRO Port Hacking Station (PH50) in surface (0m) and bottom (50m) waters for periods 1965-95 (NO₃-N) and 1957-95 (PO₄-P); 5 Tranter et al. (1986) and Cresswell (1994).

* median concentrations based on NSW EPA data collected along transects across the shelf at Pt Stephens, Pt Hacking and Jervis Bay and from PH50/100 stations at 0m (n=263) and 50m (n=170) depths for the period from August 1995 – April 1997

typical averages based on NSW EPA data 1995-97.

Notes: I reported as inorganic; NOx = nitrate plus nitrite.

Slope Water

Nutrient rich slope water intrusions (from depths >150-200m) were found to be seasonal (spring/summer peak) and episodic, operating over length scales of hundreds of kilometres and time scales of several days (Pritchard *et al.*, 1998). Slope water intrusions delivered mainly dissolved nutrients (nitrate and phosphate) and typically remained submerged, but often penetrated inner shelf waters thus elevating nutrients to the euphotic zone. Association between slope water intrusions and phytoplankton responses were suggested by Humphrey (1960, 1963) and have been illustrated by Lee *et al.* (2001 – this volume). A standing nitrate load of 420 tonnes and phosphate load of 66 tonnes would be associated with a

notional slope water intrusion 100 km in length, 10km in width (inner to mid shelf) and 30m in thickness (scale based on Pritchard *et al.*, 1998; nutrient concentrations from Table 1). A significant proportion of these loads would be rendered unavailable to phytoplankton by other limiting factors and by finite residence times on the inner-mid shelf.

Coastal Catchments

Many coastal NSW catchments have extensive estuarine systems which act as natural buffers, regulating nutrient exchanges between fresh water and ocean systems. Estuarine discharges were found to be sporadic, with high particulate nutrient loads and were dominated by the two estuaries/catchments (Newcastle/Hunter and Broken Bay/Hawkesbury) which together delivered ~40% and ~60% of catchment derived total nitrogen (TN) and total phosphorus (TP), respectively (SKM, 1997 and Figure 2).

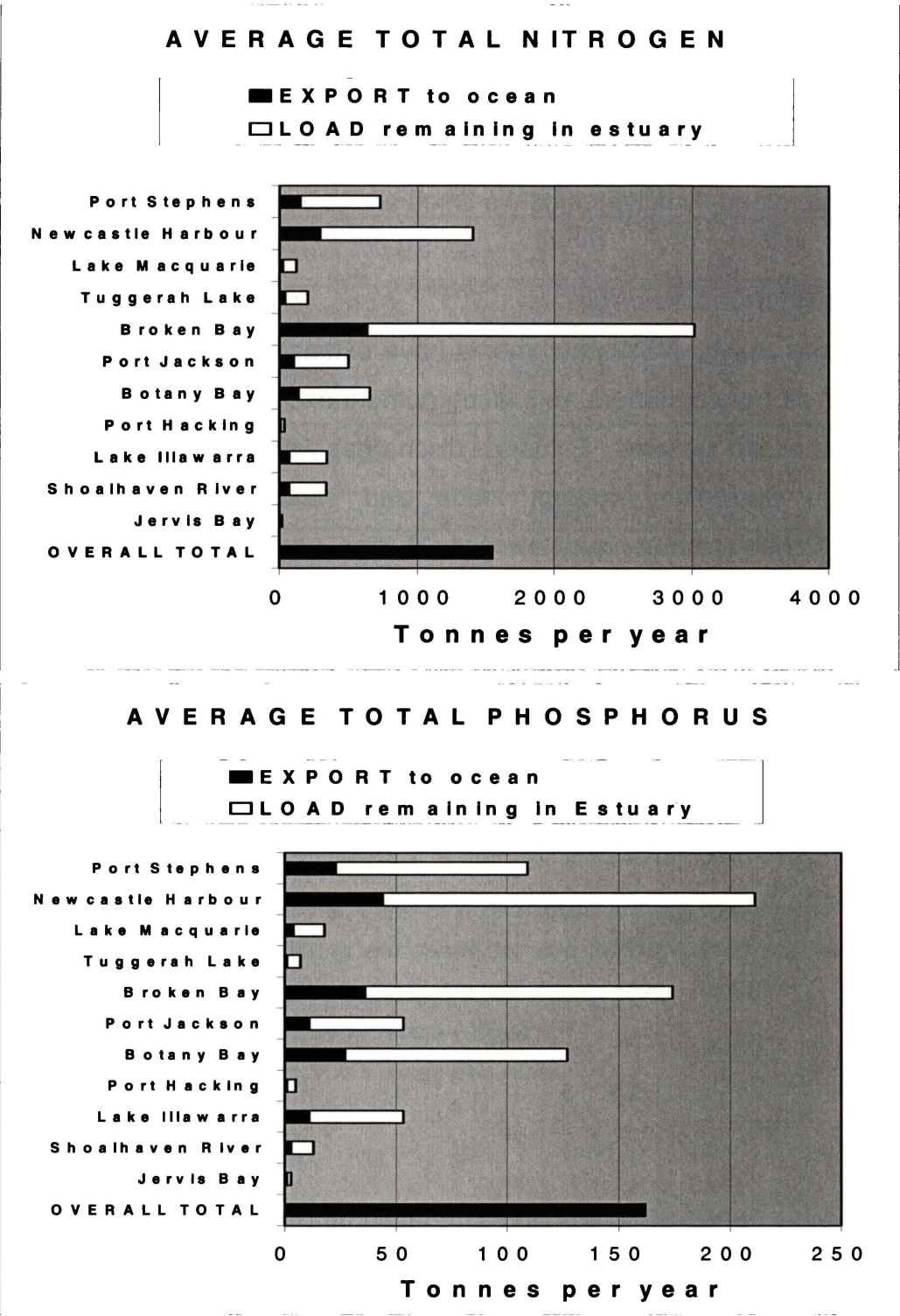


Figure 2. Indicative total nitrogen and total phosphorus loadings from coastal catchments.

Total loads were estimated as 1,600 – 7,400 tonnes/yr TN and 160 – 770 tonnes/yr TP (high ranges indicate total catchment exports while low ranges include an estimate of nutrient buffering). Extreme estuarine plumes have extended tens of kilometres for days to weeks (Lee and Pritchard, 1999).

Atmospheric and Sediment

Data from Ayres *et al.* (1987) suggest atmospheric fluxes of total nitrogen of 4.6 kg/hectare/year based on typical (1981/1982) Sydney rainwater concentrations of 170 µg/L nitrate & 210 µg/L ammonia, average rainfall of 1225mm/yr (assuming negligible organic N in air). Harris *et al.*, (1996) estimated aerial deposition to Port Phillip Bay (Melbourne) at 2.56 kgN/hectare/yr while a US review (Feth, 1966) indicated a range of 0.6-13 kgN/hectare/yr. These available data may not be representative of NSW coastal waters but indicate potential for significant atmospheric loads. Significant biological nitrogen fixation was unlikely because relevant species such as *Trichodesmium* were typically present in low densities (Ajani *et al.*, 2000) and only senescent *Trichodesmium* cells would be expected in our study region (Hallegraeff *pers comm.*, 1997).

Few relevant data were available to indicate nutrient fluxes across the sediment-water interface in our study region (Bickford, 1996) and no data were available to characterise exchanges during re-mobilisation (high wave/current) events. Such events were expected to be most relevant given evidence that the upper 30cm of the mainly sandy sediments may be re-mobilised during such events (Schneider, 1999).

Ocean Outfalls

Figure 1 shows locations of outfalls associated with sewage treatment plants (STPs) within our study region while Figure 3 indicates STP nutrient loadings from north to south. Outfalls within the study region, together, contributed 97% of the total sewage effluent discharged to NSW marine waters (~99% of total nitrogen load and ~96% of total phosphorus load). Dominant among them are Sydney's three deepwater outfalls (North Head, Bondi and Malabar) which are located in the centre of the study

area. The three deepwater outfalls together contributed about 76% of the total nitrogen and 71% of the total phosphorus.

Ammonia-N was the dominant form of nitrogen (~73% of TN) while NOx-N made a negligible contribution in primary treated sewage effluent such as that discharged from North Head, Bondi, Malabar, Cronulla, Bellambi and Port Kembla (Figure 7). Table 2 summarises nutrient concentrations observed in effluent from North Head, Bondi and Malabar STPs during 1996/97 – these results are consistent with previous available data spanning 1993-1996 (Sydney Water, 1997).

For Sydney Water outfalls discharging secondary effluent, ammonia-N, or ammonia-N and NOx-N, were the dominant forms. The relative contributions of ammonia and NOx-N varied considerably among these outfalls. Combined, ammonia-N and NOx-N made up greater than 83% of the total nitrogen. Similar results would be expected at the other NSW outfalls discharging secondary effluent.

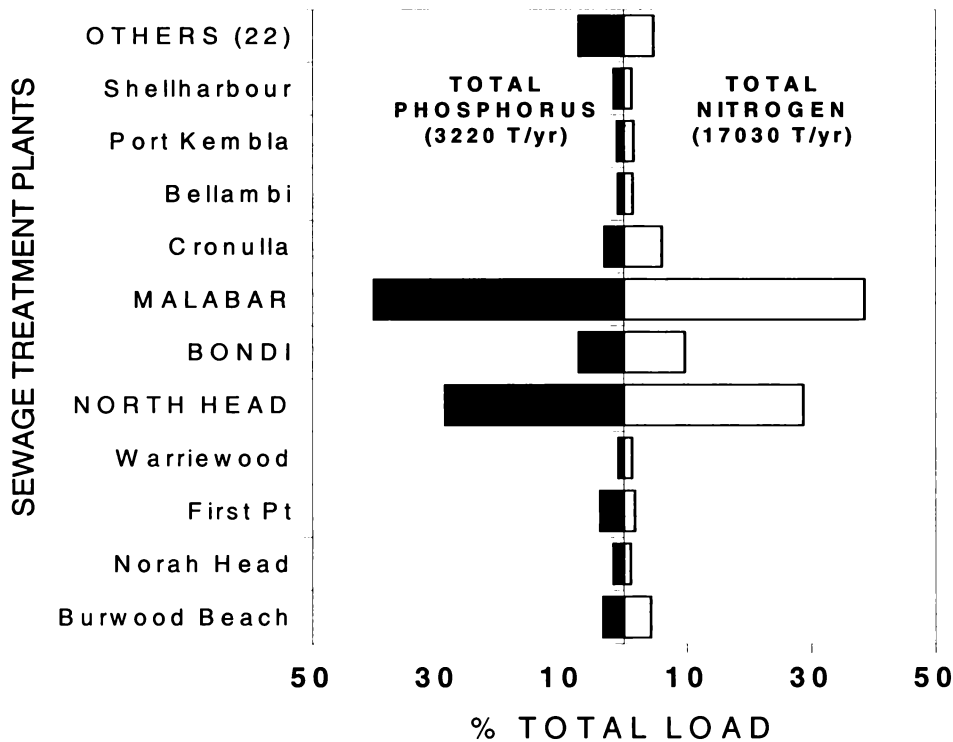


Figure 3. Total nitrogen and total phosphorus loadings from sewage treatment plants to NSW coastal waters. Data compiled for 1996/97 except 'Others' which includes data for 1991.

Much less data is available on the forms of phosphorus. Based on concentration data collected by Sydney Water in 1993/94 we would expect about 60 to 80% of the total phosphorus in primary effluent to be present as dissolved phosphorus (Table 3). The proportion would be expected to be about 85 to 95% at outfalls discharging secondary effluent. Load data for non-outfall sources were inadequate to allow statistical evaluation of apparent differences. Despite this, it was clear that nutrient loadings from coastal STPs were large with respect to other discrete sources. Based on the dominance of Sydney's deepwater outfalls and the scale of this study, further consideration of outfall effects focused on these outfalls.

Table 2 Nutrient concentrations in the effluent from Sydney's three deepwater ocean outfalls (1996/97)

Nutrient	Outfall	<i>n</i>	Effluent concentration mg/L	
Ammonia N	North Head	38	Median 32.0	Maximum 37.0
	Bondi	40	27.0	37.0
	Malabar	40	30.0	36.0
NOx	North Head	12	<0.01	0.03
	Bondi	12	<0.01	0.35
	Malabar	12	<0.01	0.07
Total N	North Head	13	44.1	49.9
	Bondi	13	36.0	41.0
	Malabar	13	39.1	44.9
Total P	North Head	12	7.50	8.70
	Bondi	12	4.45	5.80
	Malabar	12	5.40	6.60
Flow (average daily dry weather)	North Head Bondi Malabar		280ML/d 130ML/d 430ML/d	

Source: Sydney Water (1997)

Table 3 Phosphorus speciation

STP/outfall	Geometric concentration mg/L Dissolved P	mean Total P	Dissolved P as % of total
North Head	6.42	8.32	77
Bondi	3.19	4.66	68
Malabar	4.72	7.30	65
Secondary Treatment Plants (4)	4.71-7.76	5.09-8.67	86-93

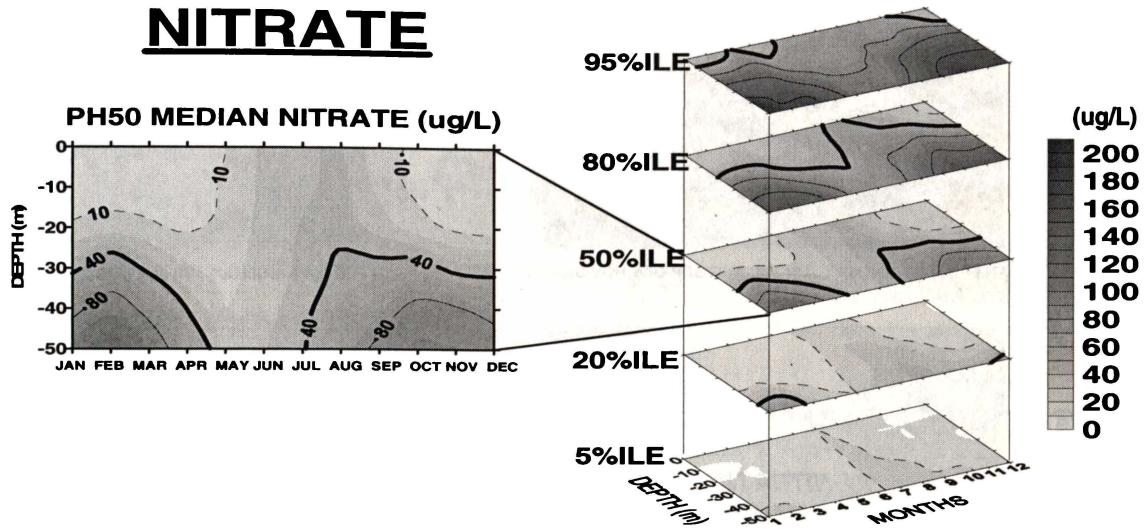
Source: Unpublished data collected by Sydney Water in 1993/94
(N=15 for each STP)

Ambient Nutrient Patterns

Previous nutrient studies in these waters have generally focused on nitrate and to a lesser extent phosphate and date back to the 1940s (eg Newell, 1966; Hahn et al., 1977; Rochford, 1984; Tranter et al., 1986; Cresswell, 1994). These studies, and our characterisation of ambient nutrient distributions prior to the commission of Sydney’s deepwater outfalls, were based (to varying degrees) on data from long term monitoring by CSIRO at station PH50 off Port Hacking, southern Sydney. These ambient nutrient data represent the combined effects of all sources regulated by biological activity.

Seasonal cycles of nutrient enrichment are apparent in Figure 4. The smallest differences between surface and deeper waters tend to occur late in the austral autumn and winter when thermal stratification was absent or weakest. During this period, nutrient concentrations in surface waters tended to be near their highest and nutrient concentrations at depth tend to be at their lowest. Maximum nutrient concentrations in surface waters occurred during July-August whilst maximum nutrient concentrations in bottom waters occurred during the summer months, peaking during February.

NITRATE



PHOSPHATE

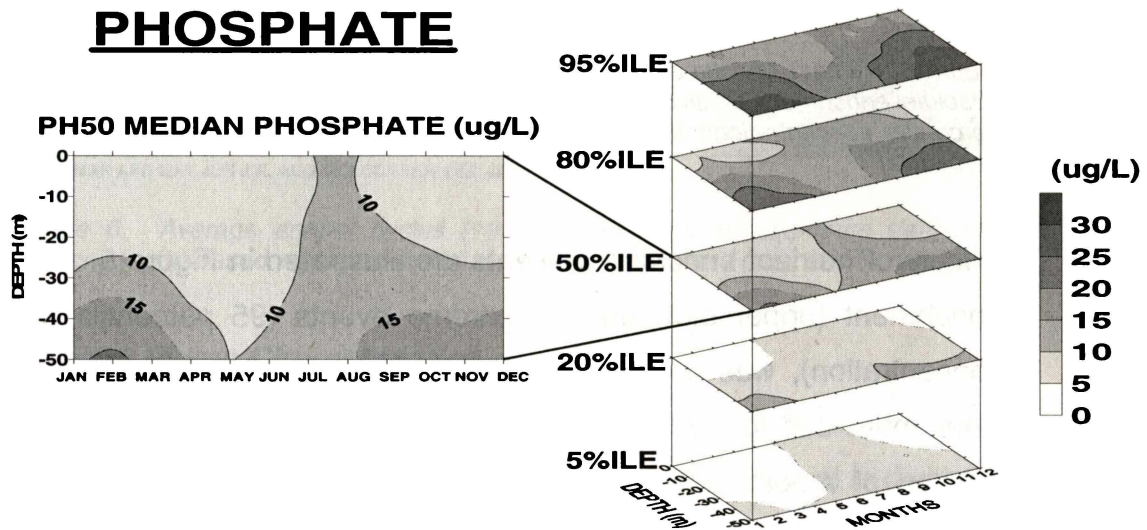


Figure 4. Ambient nutrient patterns at PH50 prior to commissioning of Sydney's deepwater outfalls (NO₃-N and PO₄-P percentile distributions).

These general patterns were evident in all percentile plots and have been attributed to winter overturning of shelf waters and episodic slope water intrusions driven by summertime EAC activity and/or upwelling favourable winds together with enhanced biological (phytoplankton) activity in surface waters during the warmer summer months.

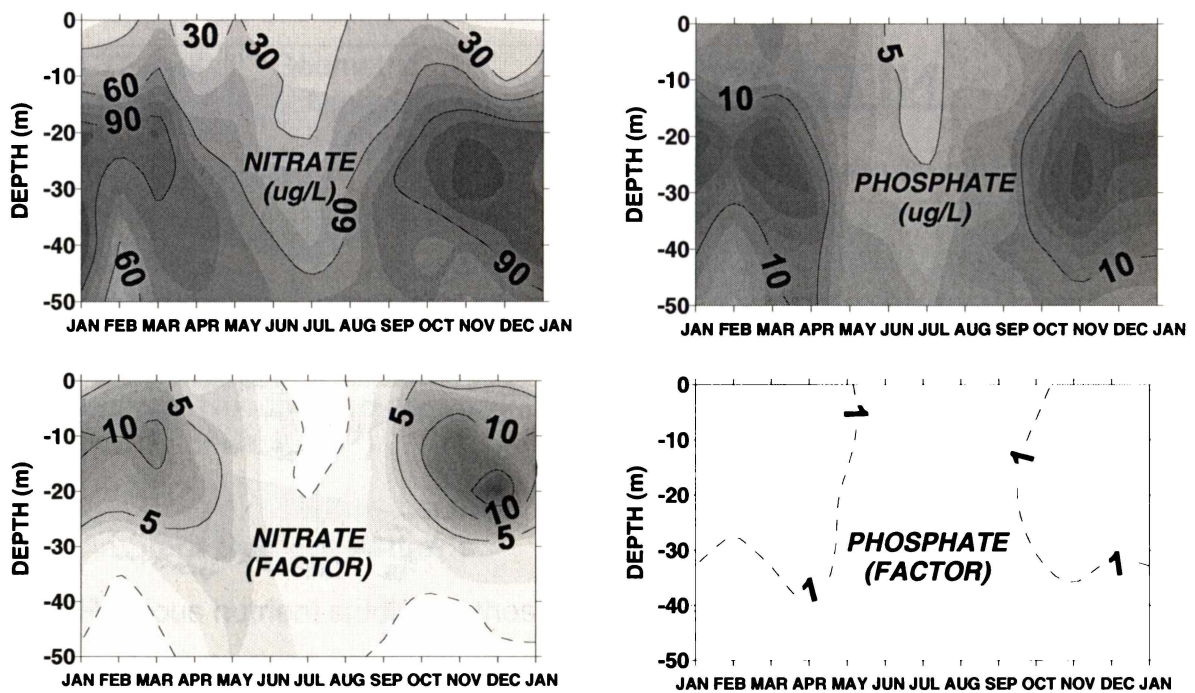


Figure 5. Nutrient enrichment at PH50 for extreme (95 percentile) events expressed as absolute enrichment relative to 50 percentile concentrations (top) and as a factor of 50 percentile concentrations (bottom) [Factor of 1 indicates 95 percentile equals 2 x 50 percentile]

Effects of nutrient enrichment events are illustrated in Figure 5. Absolute enrichment (upper plot) due to extreme events (95 percentile ambient concentration), was greatest at mid-depth (about the thermocline) from September through to April. But when enrichment was considered as a fraction of median ('typical') concentrations (lower plot) the effect was generally contained within the upper half of the water column and up to an order of magnitude greater for nitrate than for phosphate.

Outfall Effects

Nutrient fluxes across the three open boundaries of the study region remain elusive especially in the absence of comprehensive hydrodynamic data. However, local nutrient enrichment caused by major sewage outfalls can be quantified when ambient nutrient concentration patterns are considered in relation to effluent plume dynamics and known sewage effluent characteristics.

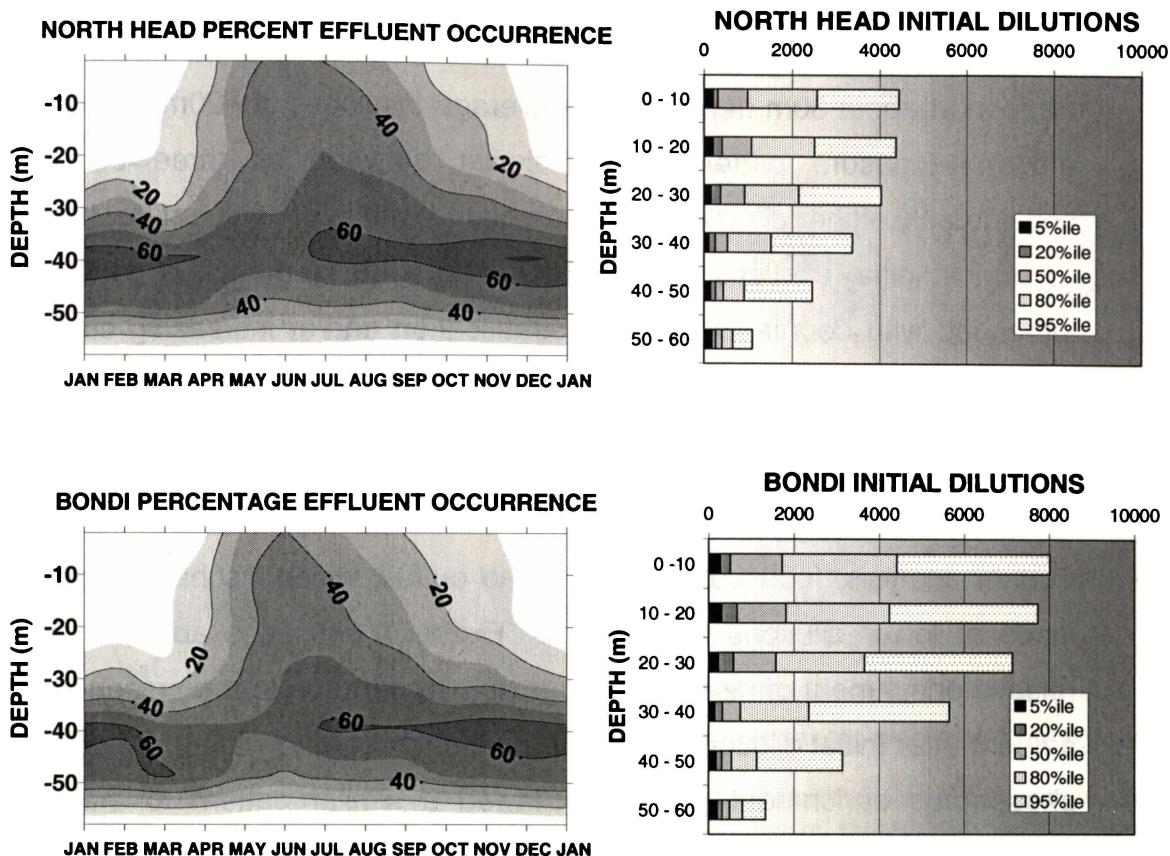


Figure 6. Average annual cycles (1991-1998) of effluent exposure (left) and initial dilutions (right) based on plume model results for North Head (top) and Bondi (bottom)

Effluent Plume Characteristics

The locations of the Sydney deepwater outfalls, which were commissioned in 1990/91, are shown in Figure 1. Effluent is discharged at high velocity from “gas burner” like diffusers that are located on the sea floor along the length of a diffuser line. The diffuser lines are orientated in a shore normal direction and range in length from 510 m at Bondi to 765 m at Malabar. Water depth is about 60 m at North Head and Bondi, and 80 m at Malabar. Because ORS data described density and current structure to just 52m depth model results were considered to be most reliable for North Head and Bondi.

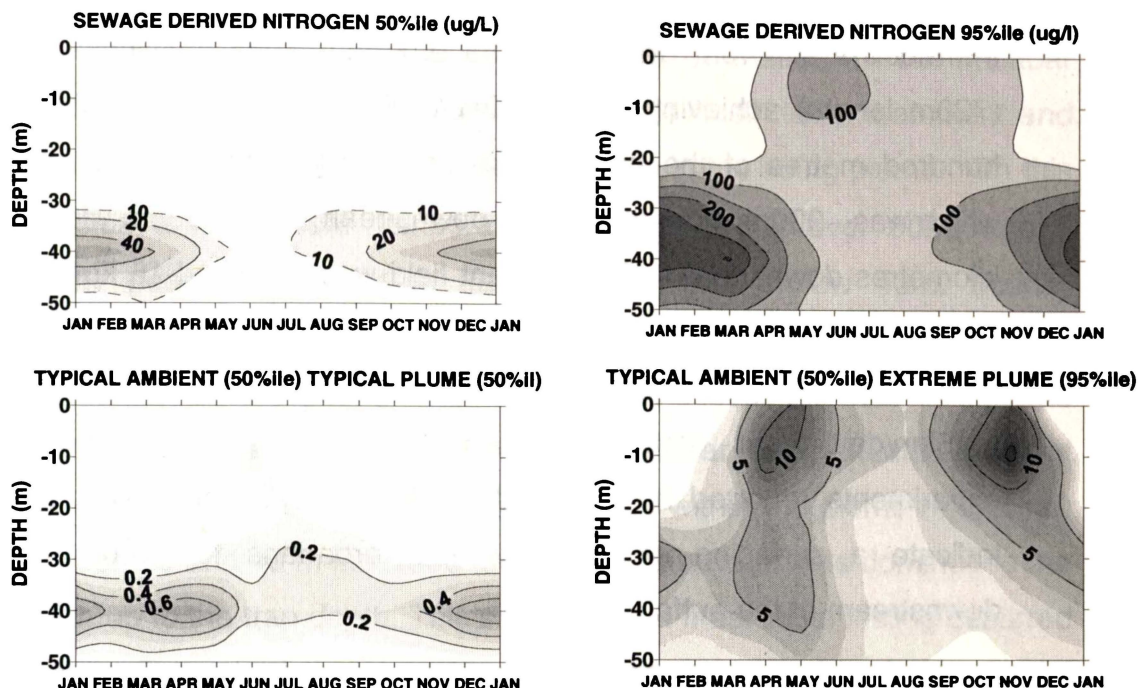
Initial dilution of effluent occurs rapidly until plumes reach neutral buoyancy (or surface), typically within 500 m of the outfalls. Figure 6 illustrates modelled effluent exposure patterns which mirror those of ambient nutrient concentrations observed prior to the commissioning of deepwater outfalls (Figure 4), and reflect ambient density stratification.

Plume surfacing was often associated with short duration (0.5 to 2 days) forcing events such as storms and internal tides. Plumes were typically trapped at about 30m depth with an average thickness of ~20m. Although effluent exposure patterns were similar between all three outfalls, considerably higher dilutions were associated with lower effluent flow rates at Bondi. Initial dilutions were lower for trapped plumes and generally increased with decreasing density stratification and/or increasing current strength.

Nutrient Enrichment due to Effluent Plumes

Further analysis, focused on North Head outfall, which discharges larger loads at lower dilutions than Bondi. Figure 7 describes absolute and relative enrichment of dissolved inorganic nitrogen due to the presence of effluent after initial dilution, relative to ambient receiving waters. Dissolved phosphorus enrichment patterns followed a similar pattern to that for nitrogen. Dissolved inorganic nitrogen was calculated as ammonia N plus NO_x N. The relative bio-availability of ammonia (principal form of N in effluent) and nitrate (principal form of N in slope/bottom water) are discussed later.

Median ('typical') and 95 percentile plume contributions are compared with median ('typical') ambient nutrient concentrations in Figure 7. Likewise, median plume contributions are compared with 95 percentile ambient nutrient concentrations ('high' - including effects of slope water) in Figure 8. The implications of these enrichment patterns are discussed later in relation to potential for algal problems.



$$\text{ENRICHMENT FACTOR} = (1/\text{DILUTION}) \times (\text{EFFLUENT NUTRIENT CONCENTRATION}) / (\text{AMBIENT NUTRIENT CONCENTRATION})$$

Figure 7. Dissolved inorganic nitrogen contribution from North Head effluent plume after initial dilution expressed in absolute terms(top) and relative to ambient concentrations (bottom) for typical plume contributions (left) and extreme plume contributions (right).

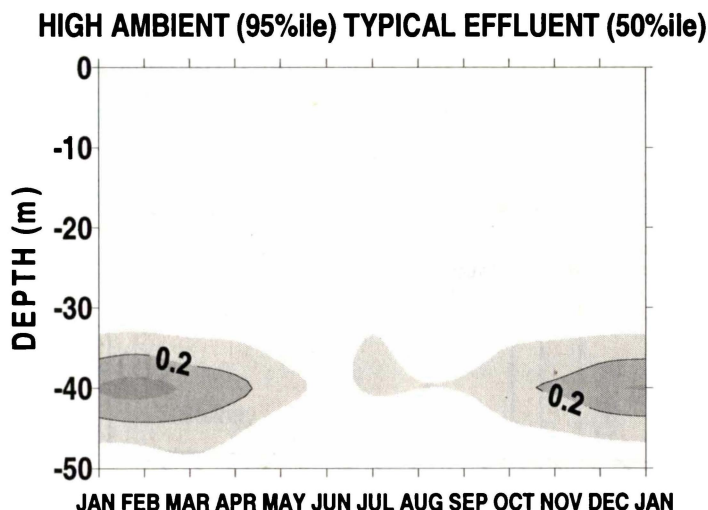


Figure 8. Typical (50 percentile) contributions of dissolved inorganic nitrogen from North Head effluent plume expressed as a fraction of extreme (95 percentile) ambient conditions such as those that may be expected during slope water intrusions.

$$\text{ENRICHMENT FACTOR} = (1/\text{DILUTION}) \times (\text{EFFLUENT NUTRIENT CONCENTRATION}) / (\text{AMBIENT NUTRIENT CONCENTRATION})$$

Spatial Extent of Effluent Plumes

Far-field modelling has shown that, after rapid initial dilution, effluent plumes tend to be advected mainly parallel to isobaths with slow subsequent dilution (Wilson et al. 1995). Figure 9 illustrates results of far field tracer studies conducted at Malabar deepwater outfall where labeled

effluent was observed as a 40m thick effluent field trapped below a 1°C thermocline at ~40m depth. Effluent emerged from the diffuser system (720m length) achieving average initial dilutions of 1:1000 within a few hundred metres of the outfall while spreading to form an effluent field which was ~900m wide, about 1km downstream and ~1950m wide, fifteen kilometres downstream. The effluent field was advected 15 km in nearly 14 hours but during this time dilution had increased to only 1:2000. Advection rates observed on this occasion were above average (~15km/day from depth averaged ORS data). In contrast tracer experiments reported by Pritchard et al. (1993) under low stratification indicate a surfacing effluent field that broadens to 2100m at 1km downstream of the outfall.

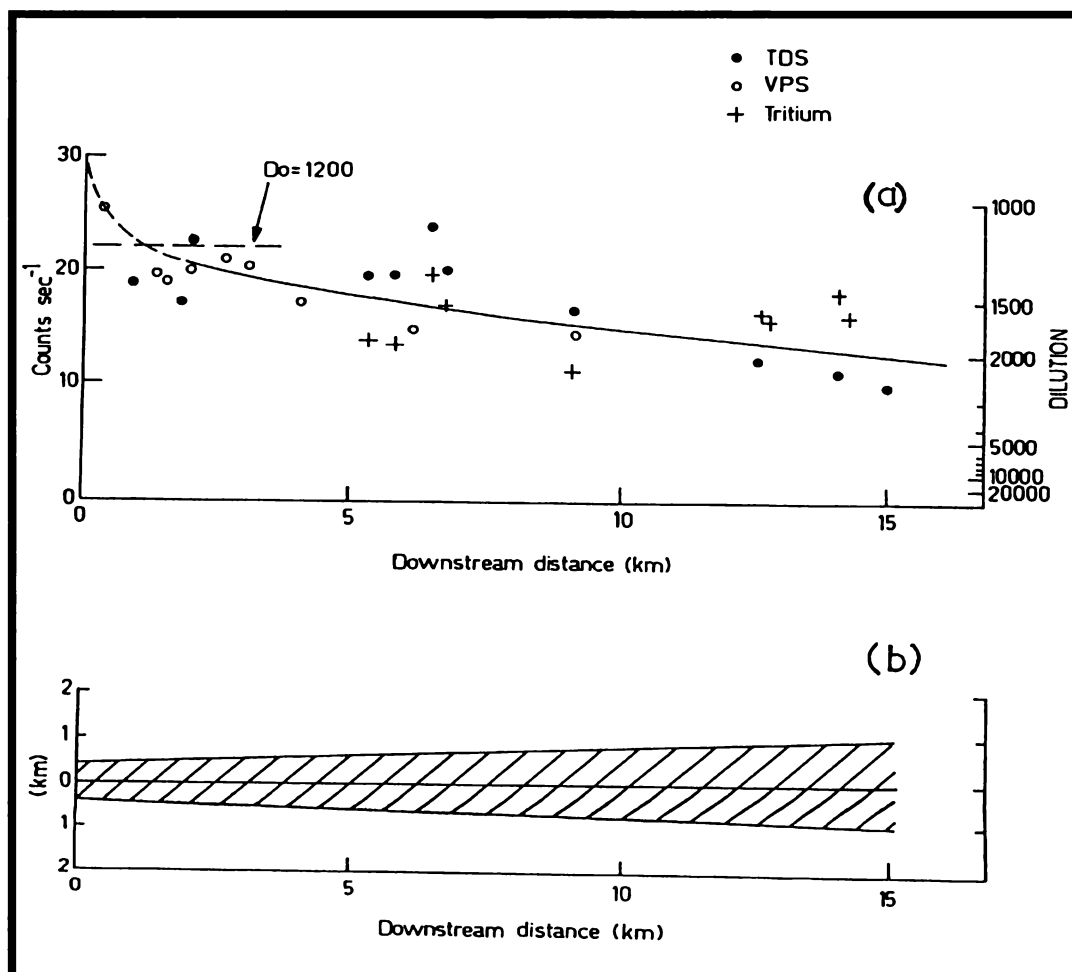


Figure 9. Far field plume (a) dilution and (b) spreading based on radioisotope tracer studies at Malabar ocean outfall on 17/06/92 when the submerged plume was tracked with a vertical triple scintillation detector system (TDS - for Gold198) and a mobile vertical profiling system (VPS) towed at varying depths through and across the plume. Water samples were collected for tritium analysis. (from Wilson et al, 1995).

Indirect Factors – Entrainment and Uplift

CTD profiles obtained approximately 500 m downstream from Malabar outfall during the summer of 1992 (Figure 10) illustrates entrainment and uplift of ambient (nutrient rich) bottom waters in the rising plume. On this occasion a near linear temperature gradient ($\sim 4^{\circ}\text{C}$ over 80m) and a salinity peak at about 40m trapped the plume below 40m. Salinity differences between essentially 'fresh' effluent ($\sim 0.1\text{psu}$) and receiving ocean waters ($\sim 35.4\text{psu}$) provide the ability to assess the near-field plume characteristics. In comparison with the linear temperature gradient observed at the upstream control, the profile within the plume (impacted) between 80 and 40 m indicated ambient bottom water was dominating the profile up to the trap depth. This suggests that most initial mixing occurred as effluent entered the ocean at 80m depth, presumably during the jet (momentum) dominated phase. Given increasing ambient nitrate (and phosphate) concentrations with depth (Figure 4), it is clear that the physical release of effluent can have an indirect effect on receiving water nitrate concentrations despite the virtual absence of nitrate in primary treated effluent. That is, the entrainment and uplift of nutrient (nitrate) rich bottom waters results in a net upward flux of ambient nutrients irrespective of the contribution from the effluent.

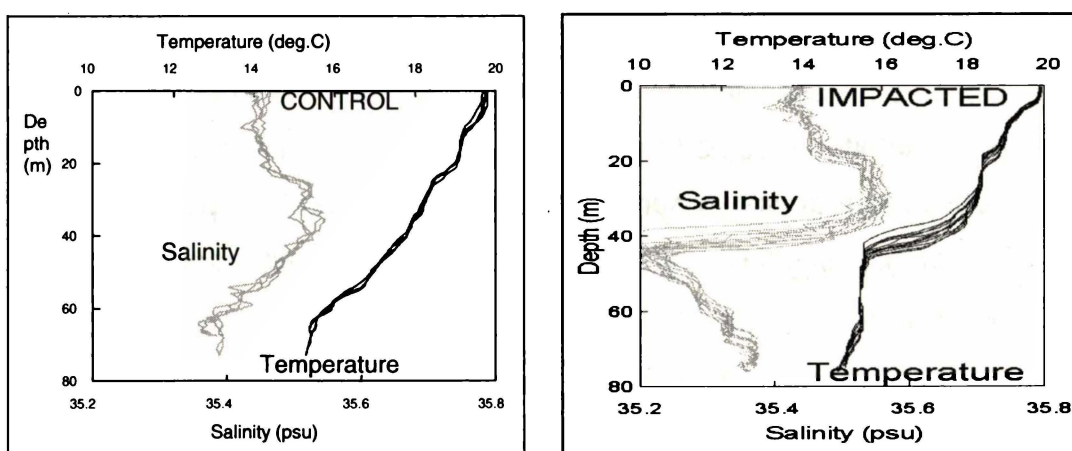


Figure 10. CTD data collected ~200m upstream (CONTROL) and ~500 m downstream (IMPACTED) from Malabar deepwater outfall during summer 1992.

Other features such as a strong effluent concentration gradient (decreasing with increasing depth) to a discrete upper boundary are expressed in Figure 10. In combination with the information from the

temperature trace, this suggests variable distributions achieved during chaotic jet dominated dilution occur prior to the rise to a level of neutral buoyancy where the plume stabilises. These observations are however contrary to the near field model simulations which do not accommodate such vertical gradients within the neutrally buoyant plume. However, possible errors in our assessment of enrichment (due to effluent plumes) were minimised by the grouping average effluent dilutions (in 2m bins) over 10 m depth intervals and mitigated by the fact that JETLAG conserves mass when estimating average dilutions.

Potential for Algal Problems

For the deepwater ocean outfalls, a consideration of only the nutrient concentrations and loads would suggest a considerable potential for algal problems. The receiving water (ambient shelf bottom water) concentrations (Table 1) are generally at or above the concentrations (in surface water) that have been associated with problems elsewhere (ANZECC 1992), and the loads of nutrients are comparatively high.

Light and nutrients, particularly nitrogen, have generally been regarded as primary limiting factors for the growth of phytoplankton in the ocean (Oviatt et al. 1989; Gibbs et al. 1991; Gabric and Bell, 1993; Pelley, 1998). Observed associations between nutrient enrichment and the phytoplankton blooms (e.g. Humphrey, 1960; Ajani et al., 2000; Lee et al., 2000) together with observed N:P ratios (Figure 11) support the notion that nutrients, especially dissolved inorganic nitrogen, are critical to the development of algal blooms in our study region.

Although high concentrations and loads of nutrients are necessary for excessive growth of phytoplankton, many other factors can limit growth (ANZECC, 1992) including mixing conditions, hydraulic retention time, light, temperature, suspended solids and grazing pressure.

Consistent associations between algal blooms and slope water intrusions and the lack of associations with proximity to major outfalls (e.g. Ajani et

al., 2001; Lee et al., 2001) led Pritchard et al. (1999) to concluded that slope water intrusions were the major factor leading to phytoplankton blooms in our study region. Despite this, potential remains for secondary effects due to sewage derived nutrients.

Phytoplankton Patterns

A range of studies off Port Hacking have found a seasonal pattern with several peaks in phytoplankton activity particularly in late summer and spring (e.g. Humphrey, 1960; Jeffrey and Carpenter, 1974; Ajani et al., 2000) These correspond to the two nutrient peaks within an annual cycle mentioned earlier. Greater phytoplankton biomass was found at the nearshore (PH50) monitoring station compared to observations at a station in 100-110m water depth off Port Hacking (PH100) (Humphrey, 1963). Phytoplankton biomass was found to be about three times that of zooplankton communities (Humphrey, 1963) with higher concentrations of phytoplankton in the upper half of the water column than in bottom waters (Grant & Kerr, 1970). Large chlorophyll peaks have been predominantly due to the >15 µm fraction, superimposed upon a nanoplankton fraction (<15 µm) which formed a more constant background level throughout the year and diatoms, coccolithophorids and green flagellates appeared to be the main primary producers at PH100 (Hallegraeff, 1981).

The phytoplankton population was found to consist of mainly neritic species (Grant & Kerr (1970). Three major phytoplankton categories were distinguished at PH100: a large group of species which were present throughout the year; a group of diatom species, which bloomed following episodic nutrient enrichments; and, a group of warm water species associated with tropical water masses (Hallegraeff and Reid, 1986)

Studies at PH100 during 1997-98 (Ajani et al., 2001) found phytoplankton blooms of similar frequency and magnitude to those seen at this location during 1978-79 (Hallegraeff and Reid, 1986). However, the high frequency of occurrence of the chain forming diatom *Thalassiosira* spp. and the 'red tide', heterotrophic, dinoflagellate *Noctiluca scintillans*

observed during 1997-98 was unprecedented in these waters. Any explanation for this change was, however, complicated by the altered physico-chemical conditions associated with the prevailing El Niño conditions that were not present in previous long-term phytoplankton studies at PH100 (Lee et al., 2001).

Nutrient Enrichment

Nutrient enrichment has the potential to effect both phytoplankton biomass and species composition – for example diatoms have high growth rates under nutrient rich-conditions (Graneli and Moreira, 1990) while flagellates do not (Oviatt et al. 1989).

Both slope water intrusions and plume dynamics were strongly influenced by ambient density stratification of the water column. Patterns of exposure to effluent from Sydney's deepwater outfalls (Figure 3), therefore, mimicked seasonal patterns of concentrations of ambient nutrients (Figure 2). Thus, 'natural' enrichment events would appear to be enhanced by contributions from deepwater outfalls. Greatest risk of outfall impacts would be expected when the contribution from outfalls is large with respect to ambient nutrient concentrations especially when ambient concentrations are low relative to saturation levels for phytoplankton growth. Figures 3 and 4 indicate that most of the nutrient loading from Sydney's deepwater outfalls remained submerged in the bottom half of the water column although under extreme (95 percentile) plume conditions effluent enrichment factors (relative to typical ambient concentrations) were greatest in the upper half of the water column during late summer and spring (Figure 4). When compared to enrichment associated with ambient extremes (Figure 8), it would appear that outfalls effects would be most apparent under specific scenarios (low stratification and low current) during late summer.

Nutrient Speciation

Both laboratory and coastal marine mesocosm experiments have demonstrated that different taxonomic groups of phytoplankton may

respond to environmental variables in different ways. Competitive differences in the ability of phytoplankton species to respond to sewage derived nutrients may provide the potential to shift phytoplankton species composition. Nitrate was the principal form of 'natural' nitrogen enrichment of ambient waters (associated with slope water) while ammonia (predominantly the ammonium ion) was the principal form of nitrogen in most of the treated effluent. Nitrate and ammonium are the primary forms of nitrogen used by phytoplankton, but nitrite, urea and other forms of organic nitrogen can also be used. Both nitrate and nitrite must be reduced to ammonium before incorporation into amino acids and other organic compounds in a cell. Under conditions of nitrogen excess, therefore, the preferred source is usually the most reduced form, that is the ammonium ion (Eppley et al. 1969a, Serra et al, 1978). The ability of a species to utilise organic forms of nitrogen varies with the habitat for which the organism is adapted. For instance, inshore, littoral and benthic species are better able to utilise amino acids and other organic forms of nitrogen than offshore species (Wheeler et al., 1974).

Cellular accumulation of nitrogen in an inactive storage form is limited in comparison to phosphorus, and when nitrogen is deficient, nitrogen compounds in cellular structures may degrade.

Filterable reactive phosphorous (predominantly phosphate) was the principal form of phosphorus in slope/bottom waters, and comprised 60 to 80% of the total phosphorus in primary treated effluent. Phosphorus uptake by algae is almost exclusively as phosphate. When inorganic phosphorus (predominantly phosphate) is low but organic forms of P are available, algae may excrete phosphatases to break down phosphorous compounds. When phosphate is available in excess amounts, cells may take it up (luxury consumption) and store it as polyphosphates for later use when external supplies are low. Therefore, under certain circumstances, the continuity of supply of phosphorus may be less critical than for nitrogen.

Nutrient Ratios

Ecosystem biomass is limited by the total amount of biochemically available nutrients through the natural stoichiometric ratios between the elements (C, N, P, S, Si, Fe, Cu, etc.) from which all living things are made. Literature cites the Redfield ratio (Justic et al, 1995) of 16:16:1 for bio-available Silica:Nitrogen:Phosphorous as the idealised ratio of nutrients for optimal phytoplankton growth. Discharges of treated sewage can alter both the quantity and relative proportions of various nutrients in coastal waters over time, which numerous studies have indicated can lead to eutrophic conditions or shift the composition and abundance of phytoplankton (Oviatt et al.1989, Graneli and Moreira 1990, Riegman et al. 1992). Ratios of dissolved inorganic N:P calculated from long term data collected at PH50 shown in Figure 11 indicate conditions that favour nitrogen limitation prior to the commissioning of Sydney’s deepwater outfalls. The time series of N:P ratios showed no clear trend over period of the data set.

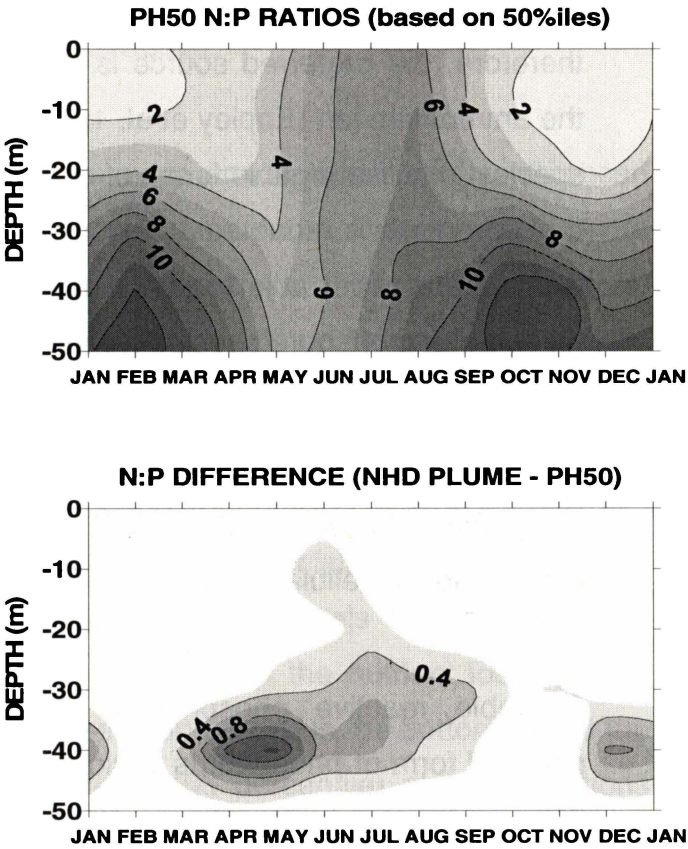


Figure 11. Molar ratios of NO_x-N to PO₄-P at Port Hacking site PH50 (top) and residual effect due to North Head (NHD) effluent plume

The annual cycle of N:P ratios from PH50 in Figure 11 indicate low ambient inorganic N:P ratios that increase towards optimal 16:1 Redfield Ratios in bottom waters during Spring-Summer when phytoplankton activity is greatest (Figure 11). Model results suggest that these ratios are relatively unaffected by the discharge of effluent from North Head outfall (after initial dilution), especially during spring/summer in the upper

half of the water column where phytoplankton activity is greatest (also Figure 11).

Other Considerations

Lee et al. (2001) demonstrated the potential for strong El Niño Southern Oscillation signals to dominate physico-chemical conditions. Therefore, long-term variability must be considered especially for impact assessments when before data are unavailable and/or where relevant control sites are unavailable/impractical.

Our investigations were based on ambient conditions defined by data with minimal ENSO bias while effluent plume data may be slightly biased in favour of El Niño, as indicated earlier. No major ENSO bias is expected although El Niño conditions may be associated with decreased thermal stratification during the winter months which promotes a slightly greater frequency of surfacing plumes and associated higher dilutions at these times (Lee and Pritchard, 1996).

The continual supply of nutrients from ocean outfalls may sustain background (low level) populations of specific plankton thus maintaining a seed stock which would otherwise be absent during sporadic enrichment events (Suthers pers comm). Effluent may be present in surface waters at high dilution for about 20-40% of the time during winter, and over 60% of the time at lower dilutions within the bottom half of the water column (Figure 6). However, when typical (50 percentile) plume nutrient contributions were compared with typical (50 percentile) ambient concentrations, enrichment due to outfalls was generally restricted well within the lower half of the water column - exceptions occur when extreme plume conditions (95 percentile) occur (Figure 7).

Conclusions

Estimates of various nutrient loadings to NSW coastal waters indicated that loadings from coastal STPs were large with respect to other discrete sources. Furthermore, Sydney's three deepwater outfalls were found to be responsible for the vast majority sewage contributions to coastal waters.

These loadings and a consideration of nutrient concentrations suggested a considerable potential for algal problems.

No new evidence has been presented to contradict previous findings that algal blooms are principally driven by seasonal oceanic nutrient enrichments. But recent studies in southern Sydney offshore waters did observe an unprecedented abundance of the chain forming diatom *Thalassiosira spp.* and the 'red tide', heterotrophic, dinoflagellate *Noctiluca scintillans*, although prevailing El Niño conditions had altered physico-chemical conditions and therefore complicated interpretations.

If there are any undetected outfall impacts, they are likely to be subtle and require more focused investigation. An understanding of physical processes operating on the continental shelf is necessary to focus such investigations because of highly variable ambient nutrient concentrations together with considerable lag times for phytoplankton (and especially heterotroph) responses. By considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns we have identified specific periods of the year and depth intervals with maximum risk of outfall impacts, especially the upper half of the water column during late summer.

Discharges from coastal sewage treatment plants were shown to contain large quantities and relatively high concentrations of bio-available nutrients. However, there is little evidence to suggest that plumes from Sydney's deepwater outfalls result in major shifts in the ratio of dissolved inorganic nitrogen to dissolved phosphorus.

Worthy areas for further research include focused studies during late summer scenarios, more detailed investigations of factors which limit phytoplankton growth, and the role of biological processes (including zooplankton interactions and bacterial processes) in cycling and sequestering nutrients.

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3-3 EXTREME DISCHARGES INTO THE COASTAL OCEAN:

A CASE STUDY OF AUGUST 1998 FLOODING ON THE HAWKESBURY AND HUNTER RIVERS

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Abstract

Many coastal catchments along the New South Wales (NSW) coast have well-developed estuarine systems which act as natural buffers, regulating exchanges between freshwater and ocean systems. Our study investigated extreme discharges from selected major catchments in the coastal zone between Port Stephens and Jervis Bay, when nutrient loadings to the ocean were well above background conditions. Preliminary assessments indicated that, within our study region, the large Hunter and Hawkesbury catchments account for ~70% of the total nitrogen and phosphorous loads discharged into the ocean. Widespread rainfalls in July/August 1998 broke drought conditions in NSW, causing 1 in 2 year floods within many coastal and inland catchments. The Hunter's narrow channel system promptly discharged flood waters as a homogenous jet to the ocean, whereas the Hawkesbury's broad and complicated estuary exhibited surface layer flood discharges occurring over a tidally maintained salt-wedge. Sampling within the Hawkesbury indicated, for over 2 weeks of flooding, that salinity intrusions were limited to the lower 20km of the estuary, with negligible loss of nutrients prior to ocean discharge. Aerial photography and SeaWiFs satellite imagery identified the flood plumes extending offshore, and were ground-truthed to estimate sediment loads in the plume. Nutrient levels confirmed the predominance of nitrate and phosphate loads that may reflect the respective geology of the Hawkesbury and Hunter catchments.

Introduction

The movement of nutrients from catchment sources to their sink in the estuary or ocean is complex. Nutrients are derived from both diffuse (agriculture, urban, forested land) and point (sewer overflows and licensed discharges) sources within a catchment. The intensity of diffuse source contamination is related to rainfall run-off processes and the interaction between flow on the catchment and the chemical and physical properties of the sediment which come into contact with the run-off. Once the flow has entered the creeks and rivers, erosive powers become significant to enhance the quantities of nutrients exported. An example of how sensitive diffuse sources are to both the intensity and volume of run-off is given by Cullen (1), where annual monitoring at Monkey Creek in the Hawkesbury-Nepean Catchment, indicated 61% of the total phosphate load was transported in 1% of the time. Wolman and Schick (2), showed that loads or sedimentation yields were inversely proportional to catchment size, so this extreme condition effect may not be so dramatic in larger catchments.

The majority of coastal catchments on the New South Wales coast have well-developed estuarine systems at their ocean end creating a natural buffer zone to ocean dynamics and chemistry. These systems also act as a barrier to direct freshwater discharge, and its associated terrestrial/anthropogenic nutrients, into the ocean, thereby increasing nutrient loss through sedimentation and biological processing prior to ocean discharge.

Catchments with large estuarine sections are dominated by strong longitudinal salinity gradients during normal flow conditions. This persistent profile is relatively insensitive to flow rate, and forms a pressure gradient that drives density currents upstream in addition to the tidal flow (Geyer and Farmer, 3). The saline intrusion becomes mixed by tidal turbulence with the overlying freshwater, creating a return surface flow. Under extreme flood flow conditions the momentum of freshwater is

sufficient to push the saline water downstream, and as the densimetric Froude number goes to unity (Hinwood, 4), the flow detaches from the estuarine floor and spreads offshore as a buoyant freshwater layer.

Data and Results

A study centred on the Newcastle-Wollongong conurbation has examined the relative nutrient inputs to coastal waters from catchments, waste discharge and oceanic upwelling. Investigations of the oceanic and sewage nutrient contributions to the coastal ocean are developed by Pritchard et al (5). Ten coastal catchments discharge to the ocean along this 300km stretch of coastline from Jervis Bay to Port Stephens. Figure 1 depicts the various catchments in the region.

These can be split physically into four main groups.

- (1) Coastal catchment with lake outlet to ocean (Illawarra, Macquarie, Tuggerah, Botany Bay, Jervis Bay);
- (2) Urban catchment (Port Hacking, Port Jackson, Port Stephens);
- (3) Large catchment with extensive estuary (Hawkesbury); and
- (4) Large catchment with delta (Hunter, Shoalhaven).

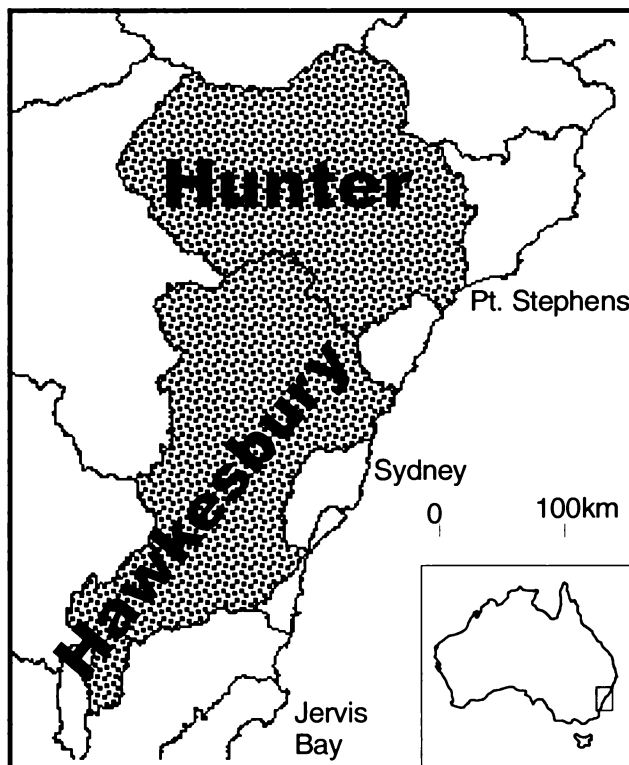


Figure 1: Locality diagram of the Hawkesbury and Hunter River catchments in NSW.

Out of the ten catchments 75% of the total catchment area is accounted for by the Hawkesbury and Hunter catchments alone. Similarly, the large Hunter and Hawkesbury catchments accounted for ~70% of the annual discharge and associated total nitrate and phosphate loads. Further investigation was therefore confined to the Hawkesbury and Hunter catchments.

Under normal flow conditions, monitoring records show that nutrient concentrations associated with the low salinity surface waters at the ocean entrance, are relatively similar to those in ambient ocean levels thereby rendering their flux as negligible. Scant information during flooding conditions suggest that nutrient levels may increase by orders of magnitude, and have different relative concentrations to the ratios found in coastal waters. A focussed study on a flood in Pt. Jackson in 1992 confirmed these nutrient increases, and monitored flood discharge to occur over twenty days (Schammel, 6). Eyre and Twigg (7) studied the flood recovery of a NSW estuary and indicated surface layer flood discharge extended some 4 days after the flood peak, but it took another month for the estuary to fully recover its longitudinal salinity gradient and nutrient distributions prior to the flood. A combination of tidal mitigation and continued nutrient discharge through pore waters lengthened the recovery time.

The 1997/98 El Niño drought conditions in NSW were broken in July/August 1998 by widespread rainfalls and subsequent flooding of both coastal and inland catchments. Weekly rainfall in late July occurred as 50-100mm falls over most of the state, whereas coastal falls of ~200mm in early August focussed on the Hawkesbury and Shoalhaven catchments. In contrast, a small flood event sampled in April 1998 had high falls focussed on the coastal fringes about Sydney with up to 200mm dropped in 24 hours, although in the heart of the catchment at Penrith, falls were a modest 10mm. With reference to long-term records from Australian Water Technology, the Hawkesbury catchment responded in the August event

with a 1 in 5-year flood level above dams, and with levels up 6m, corresponding to a 1 in 2-year flood downstream of the dams. The Hunter catchment responded with a 1 in 2-year flood with levels peaking at 9m in the freshwater section.

From this event, monitored flood discharges in the Hawkesbury occurred for over two weeks, whereas subsequent rainfalls in the Hunter maintained flood flows for some six weeks. The flood dynamics highlighted extreme differences in the mode of export to the ocean. In brief, the Hunter responded quickly to rain events, and with a narrow channel that promptly discharged flood-waters to the ocean via a narrow ~100m entrance. In contrast the classic Ria estuary of the Hawkesbury responded more slowly, and its wide 2 km entrance was further complicated by inputs from the Pittwater and Brisbane Water estuaries. The Hawkesbury catchment can have tidal excursions up to ~80 km upstream, dominating its flow dynamics with strong longitudinal salinity gradients and tidal mitigation. So freshwater discharge is often only observed in the surface layer to the ocean during ebb tide, or as a surface lens if flood conditions are sufficient to displace the upstream salinity profile. As a result the adopted sampling approaches were tailored to suit these conditions to provide a time series of flood thickness and associated nutrient concentrations at the discharge point.

Hawkesbury River

Wolanski and Collis (8) investigated the Hawkesbury during dry and wet weather events, and noted the dominance of the salinity profile mitigating seaward movement of freshwater during most flow conditions. With the cross-sectional area of the Hawkesbury channel decreasing exponentially with distance from the mouth, the saline “control” in the lower 30 km dominates the dynamics in the system.

Flood event data were collected on 10, 18, 19, 20, 22, 27 August and 1 September 1998. Data comprised of continuous CTD casts and water quality samples taken throughout the water column to quantify a surface fresh layer and the intruding saline layer beneath. Transects were taken to 45 km upstream from the entrance to monitor the dynamics of the salt wedge that dominates the estuary during normal flow conditions, and account for any changes in nutrient concentration due to sedimentation and/or erosion.

The salinity time series of transects taken during high tide periods spanning ~2 weeks is shown in Figure 2. Flood flows had pushed a freshwater pulse to within 4 km from the entrance on 10 August 1998. This retreated to a more stable position 15 km upstream during measurements on 18-22 August 1998, and resulted in the eventual development of an arrested front by 1 September 1998, thereby confining flood flows to the ebb tide. Flood-waters were sufficient to detach from the bottom and discharge as a 1-2m surface layer over the tidally maintained salt-wedge.

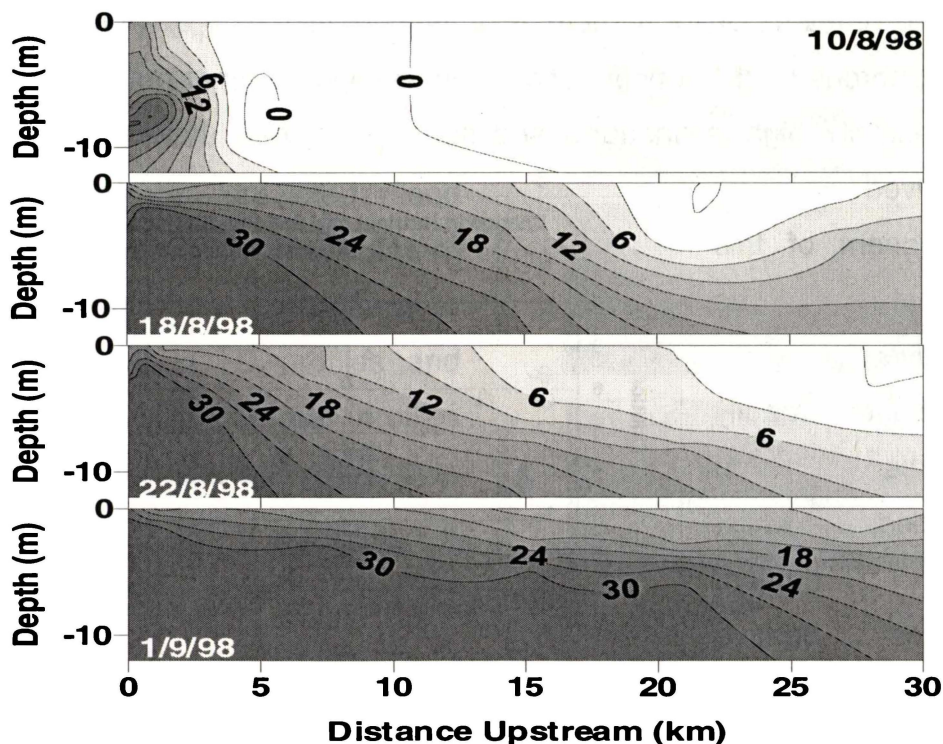


Figure 2: Salinity profiles during the August 1998 flood along the Hawkesbury River.

Table 1. Nutrient ranges 0-40 km upstream over all depths during the Hawkesbury August 1998 flood

Date	N0x ug/L	FRP ug/L	SiO ₂ mg/L	TSS _{mg/L}
10/4/98	20-80	7-10	0.4-1.6	7
10/8/98	300-400	9-12	2-4	50-200
18/8/98	150-500	10-30	1-5	20-50
19/8/98	200-600	10-44	1-5	20-60
20/8/98	100-500	14-36	1-4	20-60
22/8/98	200-300	20-15	2-3	10-100
27/8/98	100-300	10-20	1-3	30-120
1/9/98	100-300	10-16	0.6-3	6-20

Table 1, summarises the nutrients and Total Suspended Solids (TSS) associated with this flood pulse, and compares them against measurements made during a minor event on 10 April 1998. Clearly nutrients are well above the ambient levels of 10 April 1998, especially for oxidised nitrogen. Peak values for most of the flood occurs 20 km upstream coinciding with the upstream extent of the

salinity gradient. Also of note is a lagged increase of Free Reactive Phosphorous (FRP) concentrations with respect to other nutrient species. The initially high suspended sediment levels may have affected the dissolved

component of this nutrient as dissolved phosphate readily absorbs to particles, whilst other nutrient species behave

relatively conservatively.

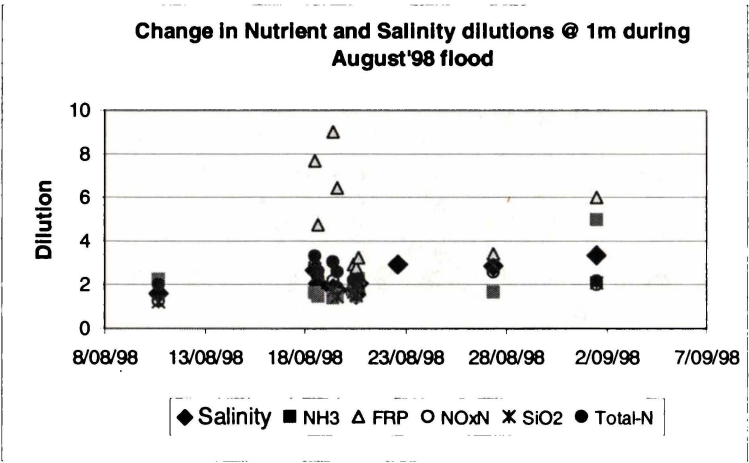


Figure 3: Salinity and nutrient dilution plot along the Hawkesbury indicating negligible loss of nutrients to the estuarine system during the flood period.

Similarly Eyre and Twigg (7) suggest the low salinities with flood-waters are responsible for increased dissolved phosphorous adsorption to iron and aluminium particles.

Ocean water content determined from longitudinal salinity transects reaching up the estuary, is shown in Figure 3. By comparing dilutions with changes in nutrient concentrations, it is possible to indicate the amount of nutrient lost in the estuarine system. Accounting for ocean dilution, sampling to ~40kms upstream in the Hawkesbury, showed there was negligible loss of most dissolved and particulate nutrients in the estuarine section during the flood event. An exception was the initial high dilutions for FRP, which may be attributed to interactions with the initially high TSS levels. By 1 September 1998 however, nutrient dilutions had increased ~ twofold for all constituents, suggesting the increased residence time due to the formation of an arrested front was responsible for enhancing nutrient 'loss' in the estuary.

Hunter River

Repeat sampling across the narrow Hunter entrance occurred over three days to capture the predicted flood peak and identify the degree of tidal control on its discharge to the ocean. CTD profiles and water quality samples profiles were taken across the 100m channel, 500m from the entrance.

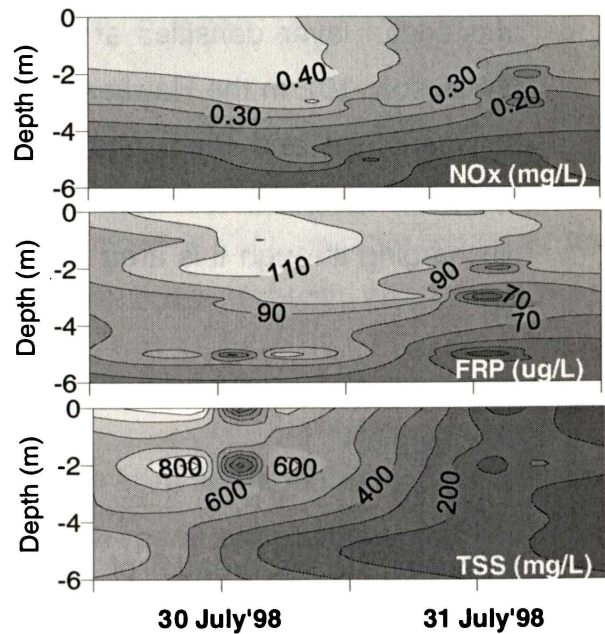


Figure 4: A time series of nutrient concentrations is given for the Hunter entrance showing the peak flood levels on 30 July associated with highly turbid water.

Upstream sampling was considered unnecessary due to the narrow and shallow outlet, and would become complicated as the channel bifurcates 1km upstream for the next 12kms.

Over this period a homogeneous fresh jet discharged offshore forming a 2m surface layer that was dispersed alongshore by coastal currents. A time series of nutrient concentrations is given in Figure 4 for the entrance station showing the peak flood levels on 30 July associated with highly turbid water.

Patterson et al (9) indicate high sediment discharges often occur from this system with an annual discharge rate of 1350 million cubic metres. TSS, FRP and silicate levels are significantly greater than those measured from the Hawkesbury, whereas nitrogen (oxidised, ammonia and totals) were similar.

Flow assessments

Flood discharges into the coastal ocean can be estimated from the flood and ocean layer densities at the hydraulic control point in the channel (Wilkinson, 10). In the Hawkesbury, the relatively narrow entrance section between Flint and Steel and Middle Head (~2 km), acts as the main hydraulic controller on river water leaving the Hawkesbury. The flow discharging through this area in the surface layer, "Qr", can be described by;

$$Q_r \sim b_H (g' h^3)^{1/2}; \quad (1)$$

Where b_H is the breadth of the entrance, h is the depth of the surface layer, and

$$g' = (\rho_{\text{surface}} - \rho_{\text{seawater}}) * g / \rho_{\text{seawater}}.$$

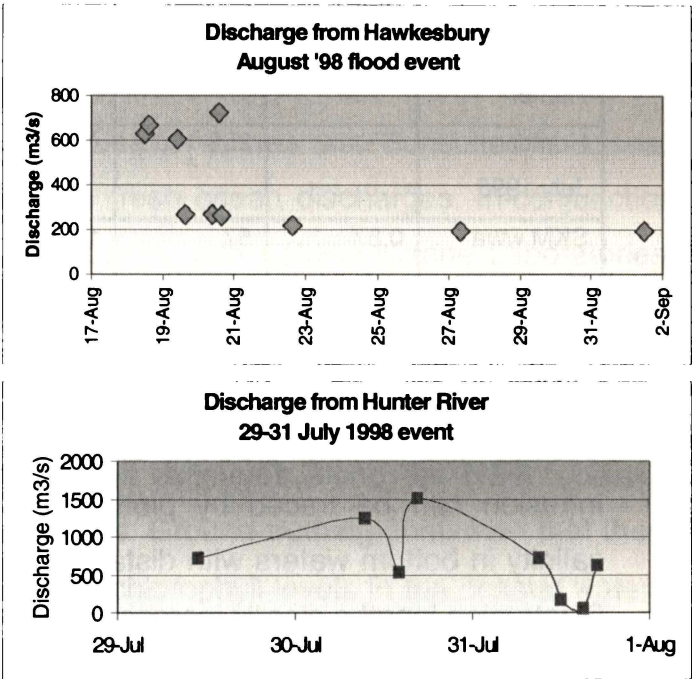
Figure 5a shows the estimated entrance discharge rates for ten transects taken on the Hawkesbury River during the August flood sampling. Of note are the large fluctuations (2-3 fold) in discharge rates attributable to tidal forcing, during focussed sampling on 20 August 1998. Discharge rates are also calculated from measurements taken during the Hunter flood, and are shown in Figure 5b. More intense sampling during a tidal cycle indicates that tidal mitigation is still a controlling factor on this predominantly fresh discharge.

Figure 5: Discharge estimates at the (a) Hawkesbury and (b) Hunter rivers during the July/August 1998 floods.

An estimate of nutrient load can be formulated by combining the calculated discharge rates from these two catchments with their respective nutrient concentrations in the flood-waters. Typical

mean event concentrations from Sinclair et al (11), referred hereafter as SKM, and the corresponding loads are compared with these flood load estimates in Table 2.

SKM adopted the 10% exceedence flow from averaged annual records as wet weather flow and combined it with mean event concentrations from the Sydney Water Stormwater monitoring project to formulate event loads. Average concentrations measured from the flood layer at the entrance during the July/August 1998 floods, were combined with discharge rates for each day of sampling to formulate a daily load estimate. Ranges of average layer concentrations and resultant loads are shown in Table 2 for



comparison with SKM's wet weather values to provide some context of the events measured. Clearly the Hunter flood is in excess of the mean event values, whereas the results for the Hawkesbury flood are able to accommodate the mean event in their range of values.

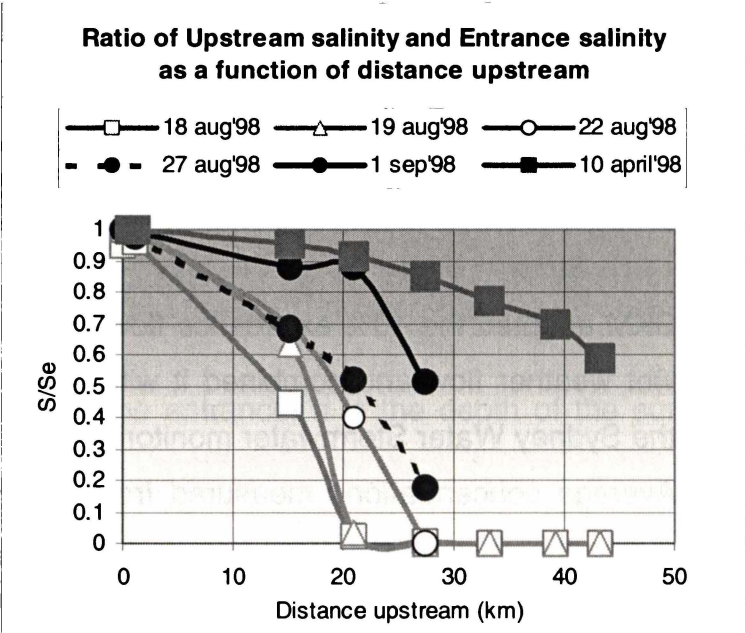
Table 2: SKM Daily wet weather averages (wwa) of total nitrogen and total phosphorous loads compared to daily loads calculated during the July and August 1998 floods.

Data Source	P-load (tonnes)	Total [P] (ug/L)	N-load (tonnes)	Total [N] (ug/L)
SKM wwa Hunter	1.3	150	8.7	1000
Hunter July 1998	27-114	250-1600	40-190	900-2350
SKM wwa Hawkesbury	0.87	57	15.1	990
Hawkesbury August'98	0.5-7	28-150	10-32	510-870

It is also instructive to compare the August event in the Hawkesbury with a small flood measured in April 1998, to look at how they

effected the salinity gradient upstream. The length of the salt-water intrusion can be traced by plotting the ratio of estuary salinity/ocean salinity in bottom waters with distance upstream. From the plots in Figure 6, intrusion lengths clearly increased as the flood subsided, although there was some fluctuation of saline dilutions in the mid-section of the estuary attributable to tidal forcing.

Figure 6: Saline intrusion lengths for the April and August 1998 "flood" events.



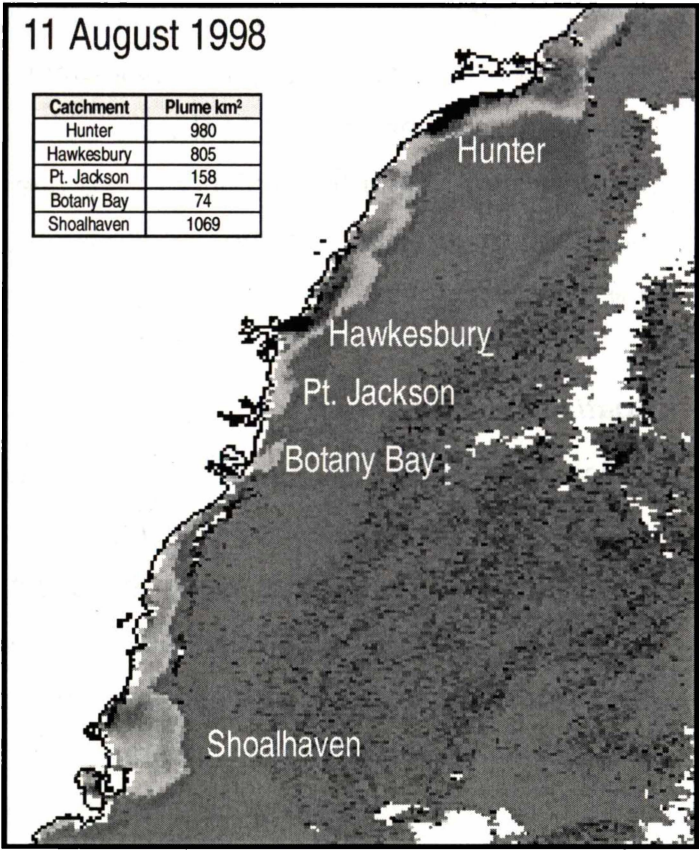
Clearly though, intrusions of 20-30 km during the August flood were less than those measured during the small event in April 1998. Salinity ratios at the 43km upstream site in April were compatible with those found 12-18 km upstream during the majority of the event in August 1998, indicating the flood had displaced the longitudinal salinity gradient by ~20 km downstream.

Spatial assessments

Aerial photography captured both the Hawkesbury and Hunter events indicating flood plumes were forming a coastal boundary layer that was being advected northwards along the coast by near-shore currents. An ocean colour scanning satellite, SeaWiFs, was also consulted to assess phytoplankton response to these fresh ocean discharges. In-conjunction with the SeaWiFS calibration program with CSIRO Marine Laboratories, Hobart, imagery was being obtained to monitor offshore phytoplankton activity for the duration of the NSW Environment Protection Authority's Ocean Nutrient and Phytoplankton Project. The images during this period indicated "off-the scale" chlorophyll estimates along the NSW coast in northward flowing plume formations. Ground-truthing confirmed that there were ambient (low $<1\mu\text{g/L}$) ocean chlorophyll levels in the coastal waters. Clearly the satellite derived chlorophyll estimates were biased by the highly turbid floodwaters that were present in NSW coastal waters, and the algorithm required improvements to filter out turbidity effects on the chlorophyll waveband. For the purposes of monitoring the floods however, the imagery provided some useful snapshots of the sediment-laden plumes emanating from their respective catchments. The image from 11 August 1998 in Figure 7, shows plume originating from five of the coastal catchments in the study region. Image analysis produced area estimates of the flood plumes from each catchment, as tabulated in Figure 7, proving a useful tool in monitoring comparative catchment discharges from a widespread flood event.

Figure 7: SeaWiFs image for 11 August 1998 indicated plumes emanating from the Hunter, Hawkesbury, Pt. Jackson, Botany Bay and Shoalhaven catchments.

An image taken earlier was used to compare with in situ offshore sample transects taken off shore from the Hunter discharge point on 30 July 1998 to look for possible



correlations with the imagery intensity scale and the in-situ water quality parameters. Looking along transect lines, band-widths within the image colour code were attributed to log ranges in the TSS measurements. Utilising the offshore plume layer thickness measurements at ~1m out to 10 km from the Hunter entrance, a first estimate of sediment load was made. The load for this image is estimated at ~7000 tonnes. Based on flood discharge rates and TSS concentrations at the entrance this figure would be reached after some 48 hours of discharge, thereby indicating that a significant amount of fallout and dispersion may be occurring in the coastal waters.

Discussion

This work has highlighted the importance of responsive monitoring to capture the critical events in Australia’s inherently variable coastal systems. Nutrient concentrations discharging into coastal waters were 2-5 times greater than the ambient dry weather conditions in the estuary, and were captured in an alongshore advecting coastal boundary layer.

Satellite imagery spatially defined this impact on the coastal environment. Detailed analysis of satellite imagery in conjunction with ground-truthing of the sediment plumes in coastal boundary layer, provided an insight to the potential to assess relative discharges from catchments, their residence times in the coastal plume and indicate sediment dispersion rates. The large scale format and high repeat orbit of SeaWiFs imagery allows multiple coastal catchment discharges to be monitored in near-real time, and could prove a value tool to support coastal zone modelling and assessments of potential coastal (offshore) eutrophication.

Long-term water quality records suggest that predominant nitrate and phosphate loads come respectively from the Hawkesbury and Hunter. Whilst the Hawkesbury catchment sits on sandstone base, a large portion of the Hunter's headwaters has basaltic bedrock. The basalt is a strong source of phosphate and may well account for the increased concentration and loads seen in the Hunter's discharge.

From the two sampled events in July/August 1998, it appears total phosphate and total nitrogen levels were enhanced in the respective Hunter and Hawkesbury catchments. As an ocean discharge though, the event in the Hunter had more pronounced concentrations and loads for all constituents when compared to measurements at the Hawkesbury.

A detailed analysis of rain events on these two systems is desirable to determine the threshold flood level necessary to make a significant discharge into the ocean. The frequency of these threshold events would then indicate the overall effect of flood plumes with respect to nutrients derived from ocean dynamics and anthropogenic coastal discharges.

Acknowledgements

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3-4 CHAPTER CONCLUSIONS

The relative comparison of estuarine and sewage sources have been provided through the findings in this chapter, showing that the sewage discharges are clearly the most prominent anthropogenic nutrient source in the study region.

However comparisons should be revisited with other sources not investigated in the field program. Based on a 1981-82 study in Sydney by Ayres et (1987), total loads from atmospheric fallout are somewhat arbitrary without knowing exact rainfall footprints over the ocean. However the measured nutrient concentrations in rainfall are low to average with respect to ambient ocean conditions for surface waters, and therefore not considered a significant nutrient source for influencing phytoplankton. Nutrient loads from atmospheric fallout and stormwater discharges are, to an extent, incorporated in the estuarine and sewage discharges. Findings show that the estuaries tend only to provide significant loads to coastal waters during flood events as the horizontal salinity gradients in their well-developed estuarine systems typically act as a buffer to discharges under normal weather conditions. Due to its age, the relatively "leaky" sewerage system in Sydney is often linked with stormwater drainage. This is obvious during wet weather when discharges from the sewage outfalls are often 2-3 times greater than dry weather flows. Whilst oceanic contributions to the nutrient budget have been touched upon in the first paper, the following chapter develops a greater understanding of the complexity to which the ocean source provides nutrient enrichments to the euphotic zone.

Chapter 4: Oceanic Processes

4-1 CONTEXT OF PAPER WITHIN THE THESIS

While typical ambient ocean conditions have been defined in the previous chapter to indicate background conditions into which anthropogenic sources discharge, the variability of the ocean source requires further scrutiny. To determine the influence of this variability within the study region, temporal and spatial dynamics of ocean processes were investigated using time series records from an array of alongshore moorings. As oceanic nutrient concentrations are typically stratified, enrichments are therefore primarily derived, either locally or remotely, from off-shelf sources. The uplifting or intrusion of these source waters is therefore the major focus in this chapter. Distinct temperature signatures of these source waters are developed to assist in the understanding of the mechanisms involved, and determine their frequency, duration, and spatial variance.

The paper has been submitted to the Journal of Continental Shelf Research for publication, and retains their specific publication format.

4-2 SCALING COASTAL UPWELLING FEATURES OF THE EAST AUSTRALIAN CURRENT

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Abstract

Twenty temperature moorings and companion current meter deployments were utilised during 1996-98 to assess the spatial and temporal variability of upwelling along 300 km of Australia's eastern continental shelf. The western boundary East Australian Current (EAC) is known to cause eddy features, and be influenced by topographic interactions, that generate coastal upwellings. Long-term data records indicate the highest frequency of upwelling occurs in austral spring and late summer. Temperature signals from the mooring array were analysed for coherence and phase, and power spectra, whilst Wavelet analysis was employed to develop an instantaneous and localise estimate of the temperature signal components. Coherent across the 300 km array were energy peaks associated with typical weather-band periods of 7-10 days. Regional events (length scales of 100 -150 km) were mostly coherent and in-phase for periods greater than 5 days. Localised upwelling events occurring at the two ends of the study region (Jervis Bay and Port Stephens) were generally incoherent throughout the frequency spectrum. Embedded within a southward cooling gradient of 0.5°C per 100 km, were observed long-shore variations in upwelling frequency. The local anomalies were related to topographically-induced upwelling around changing shoreline orientations. Alongshore regions prone to upwelling were related to sharp positive rotations in shoreline orientation, having scales in accordance with the local Rossby radius. The current mooring deployments indicated that strong upwelling at the most pronounced location (in the lee of Port Stephens promontory) was associated with frequent back-eddy formation. This eddy formation represented the peak variance/energy at that location, and was out of phase with ambient forcing experienced at the remaining mooring locations in the array.

Introduction

For many coastal ocean regions, significant upwelling of cooler nutrient-rich water occurs at the shelf break in response to persistent favourable wind which forces surface waters offshore. Akin to larger-scale coastal upwelling is more localized shelf-break upwelling induced by alongshore boundary currents that set up an unbalanced onshore-offshore pressure gradient. Embedded within these coastal currents are eddies formed by flow shear or interactions with shelf topography. These convergent circulations can locally enhance coastal upwelling by pumping waters below the nutricline to the euphotic zone. The significance of these dynamics is such that although coastal upwelling regions comprise ~0.1% of the ocean surface, they produce approximately half of the exploitable fish biomass (Ryther, 1969).

On western oceanic boundaries the mean wind field is not conducive to the persistent upwellings seen off Peru, Oregon and NW Africa. However, transient upwelling favourable winds can lead to episodic coastal upwellings when durations of the favorable weather patterns persist for a day or more, as observed on the south-eastern US continental shelf by McClean-Padman and Padman (1991). The authors noted off eastern Australia the shelf similarly experiences episodic upwelling favourable winds (from the NE sector) when high-pressure systems are situated offshore. These events usually occur during summer months and persist for several days generating a short-term coastal upwelling.

Cool water on the east Australian shelf off Sydney, was observed earlier by Rochford (1959) during autumn and early summer irrespective of wind forcing, and was considered to originate further offshore from depths of >200 m. Upwelled water 300km further to the north, was suggested by Grant (1971) to be advected by the southward flowing East Australian Current (EAC) to the Sydney region. Pearce and Boland (1982) showed that this persistent alongshore flow at the shelf break caused an onshore Ekman flux of the bottom boundary layer. This western boundary flow streams southward along the east-coast, before diverging around 32°S to

form the easterly propagating Tasman Front, and the EAC eddy field (Tranter et al, 1986). The anti-cyclonic EAC eddies advect warm Coral Sea water southward into the Tasman Sea forming dynamic thermal fronts of several hundred kilometres in length. EAC eddy shelf encroachments induce southward flows that have been observed by Pearce and Boland (1982), to enhance bottom stresses on the mid-shelf with currents in the bottom boundary layer flowing 30-40° towards the shore. Inshore of the EAC front, Cresswell (1974) has observed bottom water temperature of <13°C off Sydney in association with a southward moving cold core eddy. Anderson (1992) has observed similar instabilities on the inshore edge of the Gulf Stream that resulted in localised nutrient enrichments of coastal waters. These instabilities were thought to be primarily driven by topography. Changes in the orientation of the coastline and in local bathymetry were observed by Gill and Schumann (1979) to cause instabilities of the alongshore current, locally enhancing cross-shelf transports which lead to localised coastal upwelling in the Agulhas Current system. Off Cape Sable, Nova Scotia, Tee and Smith (1993) suggest that nutrients upwelled to the shelf by topographically driven instabilities, can be advected alongshore by a coastal current, and thereby supply coastal waters with upwelled nutrients well downstream of the upwelling zone.

To the north of the EAC eddy field (~32°S), where the EAC streams steadily alongshore, upwellings are often seen in the lee of topographic protrusions or where a narrowing of the shelf causes an acceleration of flow thereby enhancing onshore flow in the bottom boundary layer (Oke and Middleton, 2001). In this scenario it is possible for this nutrient supply to be entrained alongshore by the EAC front to the eddy field uplifting these waters to the euphotic zone, where under favourable conditions ambient phytoplankton populations can reach bloom proportions in coastal waters. Tee and Smith (1993) have identified a three-dimensional topographically driven upwelling system off Cape Sable in south-western Nova Scotia where bottom topography variations induced an uplifting of slope-waters which were advected alongshore by a prevailing coastal

current. This system allowed the upwelled nutrients to be supplied to coastal waters downstream of the upwelling zone.

Humphrey (1960), Newell (1966), and Cresswell (1994) have defined slope-water intrusions in the Sydney region based on their strong temperature–nutrient relation where temperatures are $\leq 14^{\circ}\text{C}$, Phosphates $>20\ \mu\text{gL}^{-1}$ and Nitrates $>100\ \mu\text{gL}^{-1}$. Utilizing this temperature signal to represent slope-water, Pritchard et al (2001) indicated slope-water intrudes to the inner shelf up to 6% of the time in this region. These intrusions are focussed on the spring and summer months, coinciding with the phytoplankton bloom activity shown by Hallegraeff (1981) and Ajani et al (2001). Similar use of thermal tagging in a coastal study was successfully carried out by the Canadian Department of Fisheries on their western seaboard, where thermistor arrays and long term monitoring stations were employed to infer scales of biological activity with respect to seasonal upwelling (Hsieh et al, 1995; Thomson and Ware, 1996; Whitney et al, 1998).

The study presented in this paper expands the knowledge of slope-water intrusions in the region of the EAC eddy field by examining the thermal structure to infer temporal and spatial scales, and relate them to the prevailing coastal upwelling processes.

Data and Methods

Weekly to monthly sampling runs at Port Hacking, Sydney, have been in operation since 1942 by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) collecting temperature, salinity and nutrients through the water column at two stations, PH50 and PH100, located in 63 m and 105 m of water respectively (see Figure 1). As the PH50 time series has consistent data coverage over depth, and is at a compatible depth to an instrumentally monitored station to the north (the Ocean Reference Station), this study will neglect the PH100 record. The PH50 station was sampled at 0, 10, 20, 30, 40 and 50 m depths. Free

Reactive Phosphorous (FRP), Oxidised Nitrogen (NO_x-N) and silica were the predominant nutrients analysed from these samples.

On-going monitoring at the Ocean Reference Station (ORS) in 65 m water depth ~3 km off Bondi, provided 5, 60 and 720 min quality controlled current and temperature data in the depth profile. This instrumented buoy consists of two InterOcean S4 current meters (accuracy 0.01m.s⁻¹, +/- 0.5°, and 0.02°C) at 17 m and 52 m depths, an RM Young anemometer (accuracy 0.01m.s⁻¹ and +/-1°) 5 m above sea level on the buoy, and 16 Aanderaa thermistors (calibrated to 0.1°C) strung from below the buoy to the 52 m current meter. This facility, operated by Sydney Water, has been in operation since July 1989. This excellent record of almost ten years allows some historical context for the thermistor sampling in 1997/98.

Utilising the temperature signal of slope-water intruding on the shelf, twenty thermistor moorings were deployed between Port Stephens and Jervis Bay during the period of July 1997-August 1998, to characterize the frequency and duration of slope water intrusions to the inner shelf. All instrumentation was located along the inner continental shelf, in water depths of 50-100 m (Figure 1). Each thermistor mooring consisted of three StowAway® temperature loggers (*range -5 °C to 37 °C; accuracy 0.1 °C*), positioned at 2 m, 10 m and 20 m above the bottom. The optimal depths for the loggers to capture upwellings were determined from a cursory assessment of the upwelling frequency at long-term monitoring stations off Port Hacking (in ~50 and 100 m water). All thermistors sampled hourly in synchronicity. Each thermistor was calibrated in an insulated ice/water bath prior to deployment by logging the zero offsets, according to manufacturer's instructions. Of the twenty moorings deployed, a full 12-month record was recovered from fourteen moorings.

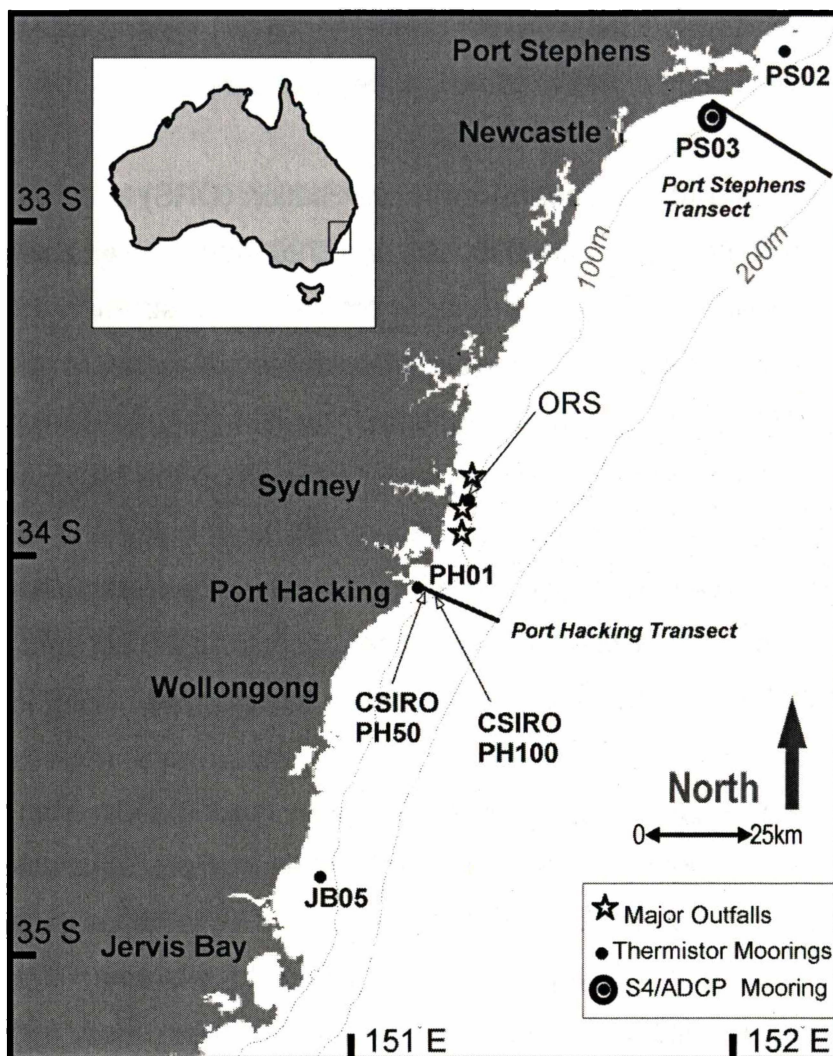


Figure 1: The NSW coastal study region between Port Stephens and Jervis Bay marked with the long-term monitoring sites PH50 and ORS and specific mooring locations deployed during 1997 and 1998.

To assess latitudinal variance of temperature and nutrient criteria in source slope-water, a compilation of hydrographic data beyond the shelf was acquired for 31 to 35°S between 1965 and 1997 from scientific ship cruises by the CSIRO's Marine Laboratories (CSIRO database).

During the study period, the National Ocean and Atmospheric Administration (NOAA) Sea Surface Temperature (SST) satellite data, and Sea-viewing Wide Field-of view Sensor (SeaWiFS) chlorophyll-a reflectance data for NSW coastal waters were accessed through the CSIRO remote sensing facility in Hobart, Tasmania. SST imagery was examined for regional circulation patterns that may promote coastal upwelling, whilst SeaWiFS was monitored for phytoplankton bloom activity indicative of a coastal enrichment.

The CSIRO were commissioned to run a data assimilation model to infer along-shelf thermal structure within the study region. The model produced a 10-day repeat time series of temperature covering the period from October 1992 to July 1997 (Ridgeway and Dunn, 1998). The 5-year record of simulated temperature field from CSIRO's empirical model incorporated NOAA SST satellite data, Topex/Poseidon satellite altimeter data and coastal sea level data from tide gauges in Jervis Bay, Wollongong, Sydney and Point Stephens, and interpolated them into a 0.1° grid (Ridgeway, 1996, Ridgeway et al, 1997). The model resolves thirty-six elements in a ~300 km alongshore slice between Jervis Bay and Port Stephens at the 125 m depth contour.

An S4P current meter was deployed in the previous summer season (Nov'96 – Feb'97) at the PS03 site where strong upwelling/uplifting dynamics were sensed during transect work from earlier studies in the 1995/96 summer (Lee et al, 2001b). A review of NOAA SST imagery indicated upwelling dynamics were often present as the EAC stream flow passes south of the Port Stephens prominence (Point Stephens), suggesting this to be an interesting site for a current mooring. The meter was placed 2 m off the bottom in a water depth of 61 m, recording 5 minute averages every 30 minutes. For continuity, a 300KHz RD Instruments Acoustic Doppler Current Profiler (ADCP) was deployed during the thermistor array campaign at the same location. The ADCP was gimbed in bottom mounting at 60 m depth, and sampled 1m depth-averaged bins every 15 minutes. The system was deployed on 2 October 1997 and retrieved for servicing on 4 December 1997. Failure of the recovery system and heavy fouling required the housing to be re-built, which negated further deployment during the summer season.

Approach to analysis

In order to examine upwelling events, it is necessary to understand the mechanisms of slope-water intrusion, and in particular the temporal and spatial scales of coherent intrusion events.

Initial assessment was therefore made on existing data from the PH50 records, the ORS, CSIRO cruise data 1965-97, and the current mooring at Port Stephens. The 9-year time series records from the ORS provided a good basis to define upwelling durations in the study region. A prescribed slope-water temperature threshold ($\leq 14^{\circ}\text{C}$) confirmed by Lee et al (2001a) from the 57-year record at the nearby CSIRO Port Hacking stations (~25 km to the south), was utilised to assess conditions during slope-water events at the ORS. To provide an insight into defining remote and localised upwellings experienced at the ORS, current components for upper and lower layers were correlated with temperature and wind. Cross-shelf transect data collected at Jervis Bay, Port Hacking and Port Stephens by Lee et al (2001b) however indicated a combination of localised and regional slope-water intrusion events were evident during the upwelling seasons of 1995-97.

The 1996-97 current moorings placed ~150 km to the north of the ORS at Port Stephens confirmed that there were low frequency events that correlated to ORS records, but localised features were equally prevalent. Through the placement of thermistor moorings at carefully selected sites over 12 months, an investigation of localised influences on slope-water intrusions was then considered possible. This was initially conducted through frequency and duration plots, together with a comparison of mean statistics. Monthly slope-water intrusion events were arbitrarily defined as water masses meeting temperature threshold criteria for a minimum of 12 hours, with lapses of 4 hours or less permitted in the data. As a fixed temperature threshold criteria appeared inappropriate for the whole study region, the relationship between temperature and phosphorus (FRP) and nitrate (NO_x) nutrient ranges from the cross-shelf transects on the shelf (Lee et al, 2001a) and CSIRO cruise data at the continental slope were combined to quantify regional variance.

With the analysis of the thermistor mooring data, the cross correlation between observations of two time series is of interest. In such analysis, the lag represents temporal and/or spatial differences between the two

records as quantified by the temporal offset between the zero delay correlation and the maximum correlation of two data sets. This would indicate how similar the two temperature data sets were, supplying information as to the spatial extent of temperature coherence along the NSW coast. The autocorrelation coefficient measures the correlation between successive observations of a single variable and thus implies the degree of agreement within a single data set. Autocorrelations conducted for each thermistor mooring assist in defining the length of the intrusion event, and are compared with observed durations of slope-water intrusions in the region. The variance of the temperature data sets were determined by shifting a 20-day window along each time series, and for each window position, the mean was removed and the variance calculated.

The use of Fourier analysis to calculate power spectra is an important tool for examining the periodic components that dominate a time series. Prior to analysis, the raw temperature data collected from the thermistor moorings was filtered to remove the mean and trend. Due to the need for statistical reliability of spectral estimates, the data was separated into 56-day segments with a 28-day overlap, and a power spectra was calculated for each segment at selected mooring sites. From this, a comparison of peak frequencies and seasonal differences in the three coastal regions was possible.

Wavelet analysis is advantageous over Fourier analysis for developing an instantaneous and localised estimate of the signal components, as opposed to the averaged and smoothed values generated by the Fourier technique (Emery and Thomson, 1997). The type of wavelet selected for analysing the temperature data was a continuous Biorthogonal wavelet, with a taper added to extend each end of the time series, thus assisting to minimise the side-lobe distortion caused by non-periodic behaviour at these locations. The total length of the buffered time series remained a power of two. The wavelet was stepped through the time series, with scales ranging between 2 and 2048.

The Biorthogonal wavelet was selected after trialing several other wavelet algorithms, such as the Morlet and Symlet wavelets. Difficulty in detecting motions accurately comes from the plethora of scales at which they occur, and also from the inevitable background of noise. The magnitude of the wavelet coefficient reveals the degree of similarity between the signal and the wavelet function. A criticism of applying wavelet analysis is the arbitrary choice of the wavelet function, and thus it is intuitive that the interpretation of the wavelet coefficients depends greatly on the choice of the wavelet function. The selection of the Biorthogonal wavelet for the analysis of this data set, is justified here on the basis of the similarity between the original time series and the function, and the accuracy of this wavelet to return the desired wavelet scale when tested with an input signal of known parameters.

Our earlier assessments of the thermistor records, identified four coherent regions that could represent the study area, being the PS02, PS03, PH01 and JB05 50m moorings. For most of the analysis we have focussed on these four unbroken 12-month thermistor records.

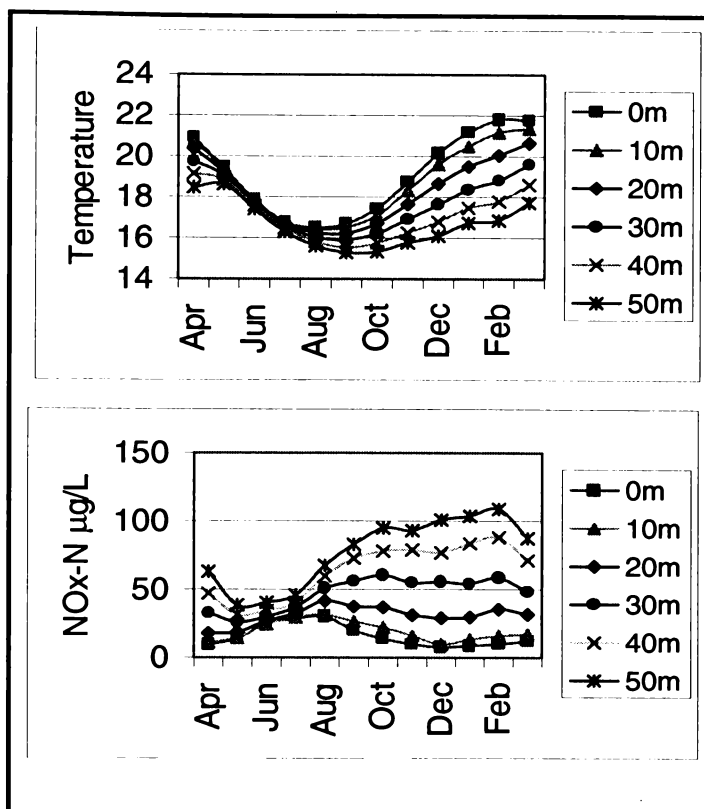
Results and Discussion

The long-term temperature and nutrient records (since 1942) from the Port Hacking sampling station (PH50) off Sydney, are shown in Figure 2 as averaged annual curves for each sampling depth. They indicate surface water nutrient maxima occur in early spring associated with winter cooling, and bottom water nutrient maxima relating to summer intrusions of cool water. The summer maxima's are typically three-fold the concentrations of the winter maxima. Studies by Ajani et al (2001) and Hallegraeff (1981) in shelf waters off Sydney, Australia, relate the seasonal patterns in the physico-chemical data with algal blooms occurring predominantly in early spring and late summer. The enhanced algal response to the summer intrusions mirrors the elevated nutrient climate during this period. The focus of our study is predominantly on these intrusions.

Analysis of ORS data investigated the wind/current/temperature associations to assess relative forcing mechanisms for coastal upwelling.

Figure 2: Seasonal dependence in the region indicated from averaged temperature and nitrate annual cycles at the long-term monitoring site PH50.

Three possible upwelling scenarios could be delineated from the ORS record based on associations of parameters measured at the ORS. These are locally wind-driven, local



geostrophic forcing and remote upstream EAC driven upwelling.

Locally wind-driven upwellings are typified by persistent winds from the northerly quadrant associated with offshore surface and onshore bottom water transport (McClellan-Padman and Padman, 1991). Local geostrophic forcing is indicated by elevated alongshore currents, increased surface water temperatures, and onshore flow at depth. The intrusion supply from a remote upwelling is suggested by an ambient alongshore flow exhibiting a lack of local dynamics (e.g. no onshore flow at depth, no favourable winds). The 1991-1999 ORS current and temperature records were initially assessed to identify characteristic physical forcing (wind and currents) conditions associated with events of cool bottom waters at the inner shelf. For the purposes of this exercise slope-water temperature has been “relaxed” from the $\leq 14^{\circ}\text{C}$ criteria (based on analysis of long term data at CSIRO Port Hacking stations) to $\leq 14.5^{\circ}\text{C}$. This adjustment accommodates a $\sim 0.5^{\circ}\text{C}$ discrepancy in bottom waters between the Port Hacking records and the ORS indicated by Lee et al (2001a). Figure 3 compares tidally filtered ORS data for cool water conditions ($\leq 14.5^{\circ}\text{C}$) to the overall 9-year ORS record. Enhanced temperature stratification (ΔT all > 2), and southward onshore flows in the upper layer (94% of the time) of the water

column emerge as the strongest features associated with cool water events. Localised intrusions of slope-water, indicated by onshore flow in the lower layer associated with slope-water temperatures, was not resolved. Wind components (shown as direction to) only suggest a marginal tendency for upwelling favourable winds to be associated with cool water conditions. These results suggest slope-waters experienced at the ORS, off Sydney, are predominantly advected alongshore to the ORS from a remote upwelling source to the north of the region.

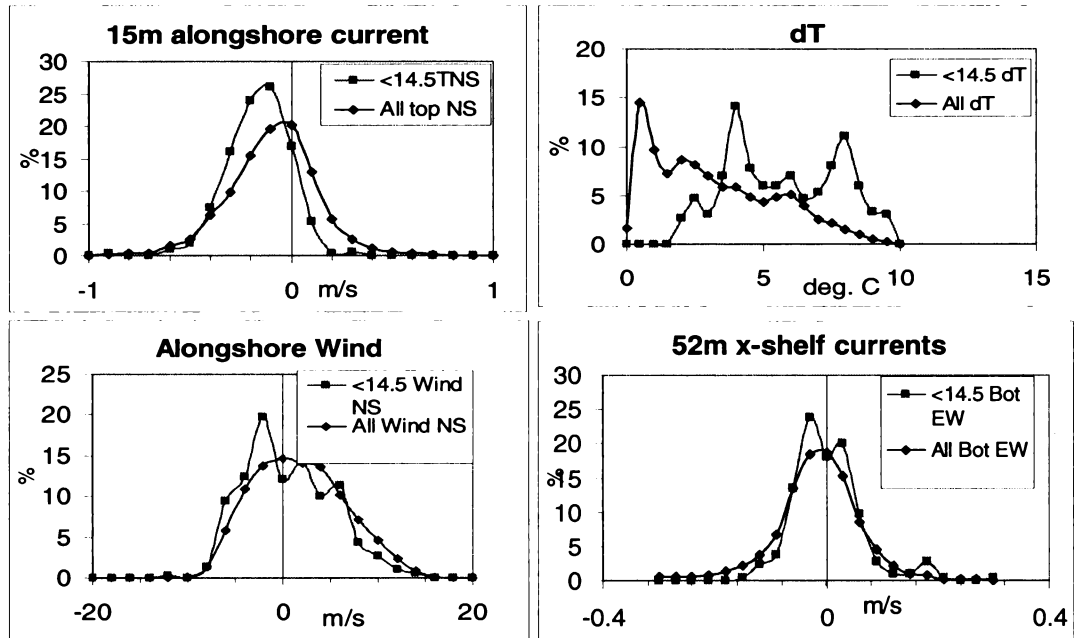


Figure 3: Comparison of alongshore currents, wind, stratification and cross-shelf bottom currents for intrusion temperature criteria ($\leq 14^\circ\text{C}$) with respect to all data for ORS records between 1991-99.

Thermistor array scaling

As an introduction to the thermistor data record collected, a cursory assessment is provided to identify the main features captured during 1997/98. Figure 4(a) plots the frequency of bottom water temperature from a selection of the 50 m mooring sites representing the entire study region. Focussing on the cooler end of the distribution where our interest with slope-water lies, a coherent peak is apparent with a northward decrease in strength (18-10%) by Port Stephens, and increase in temperature (15-16°C).

Aligned with this northward trend is the evolution of a second warm peak that increases at the expense of the major peak. Overall distributions are more consistent over the 150 km between Port Hacking and Jervis Bay, whereas a distinctly different bimodal distribution for the northerly sites around Port Stephens strengthens presumably from the greater influence of warmer EAC waters. From these plots it is clear that the $\leq 14^{\circ}\text{C}$ upwelling temperature criteria, devised for the Port Hacking location, may not be applicable for locations further alongshore.

Figure 4(b) summarises alongshore variations of bottom waters, utilizing the thermistor records at ~ 50 m depth from fourteen moorings (50 and 100 m moorings) during the 12 month deployment. In general, an alongshore cooling trend of $\sim 1.5^{\circ}\text{C}$ to the south is indicated. The medians identify two steps in this southward gradient. The northernmost PS02 site has a median of 17.3°C , which reduces over 100 km by 1.1°C . A second peak of 16.6°C starts at PH01, and reduces over 150 km by 1.3°C by Jervis Bay. While the frequency of $\leq 14^{\circ}\text{C}$ water, shown in Figure 4(b), also displays this cooling, it more importantly identifies amplitudes of longshore variance at scales of ~ 100 km that suggest localized regions of prominent upwelling. From cross-shelf transect data taken off Jervis Bay, Port Hacking and Port Stephens during 1995-97, Lee et al (2001a) had also indicated there was alongshore differences of $\sim 1.5^{\circ}\text{C}$ (with respect to prescribed upwelling nutrients), with the majority of this change occurring between Port Hacking and Port Stephens.

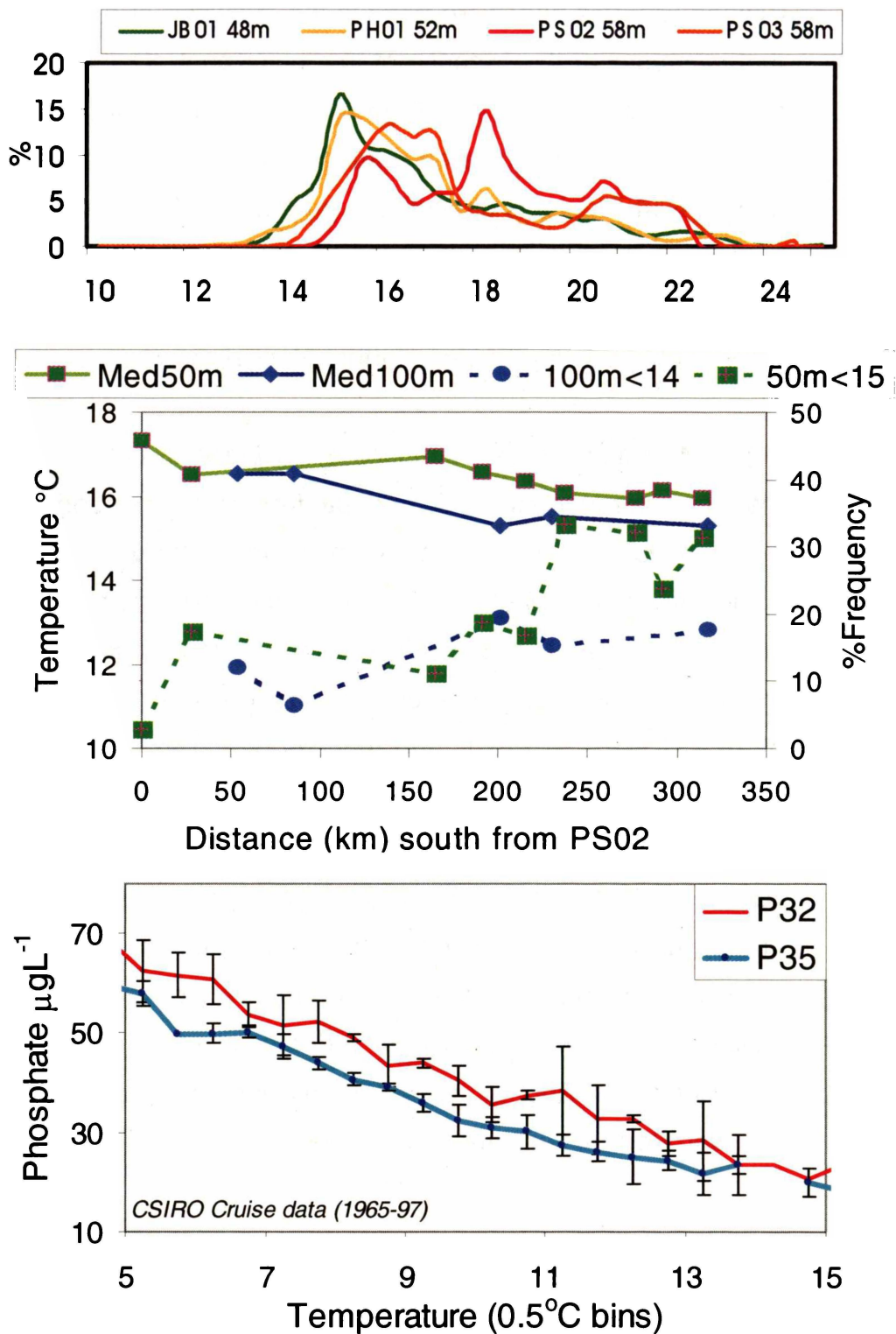


Figure 4: (a) Temperature frequency from representative moorings in the Jervis Bay, Port Hacking and Port Stephens regions, suggest varying climatology in the region. (b) median alongshore temperatures and slope-water frequencies at 50m from 14 mooring locations over 1997/98, and (c) Phosphate-temperature relations from source slope-water at 32°S and 35°S .

These differences could be due on-shelf heating, as shelf widths decrease southward at these three locations (Port Stephens - 45 km, Port Hacking - 25 km, and Jervis Bay - 20 km). To resolve this discrepancy, the source slope-water was examined for alongshore cooling. CSIRO cruise data (1965-1997) from beyond the 200m contour at depths >200 m were binned latitudinally between 32°S and 35°S. Temperature-nutrient relations plotted in Figure 4c, for phosphate, show significant differences of ~1°C between the respective 32°S and 35°S latitude bins for waters ≤14°C.

The mooring data has highlighted both this alongshore trend, and, to a greater degree, the effect of EAC interactions with irregularities in the alongshore topography. The alongshore T-N trends in both the source slope-water data and cross-shelf transects, confirms the need to modify slope-water temperature thresholds for the mooring records. Based on these findings, the yearly temperature record was binned into months and percentage occurrence plots based on threshold criteria of $T \leq 13.5$, 14.0 and 14.5°C for respective Jervis Bay, Port Hacking and Port Stephens moorings. The results are displayed in Figure 5.

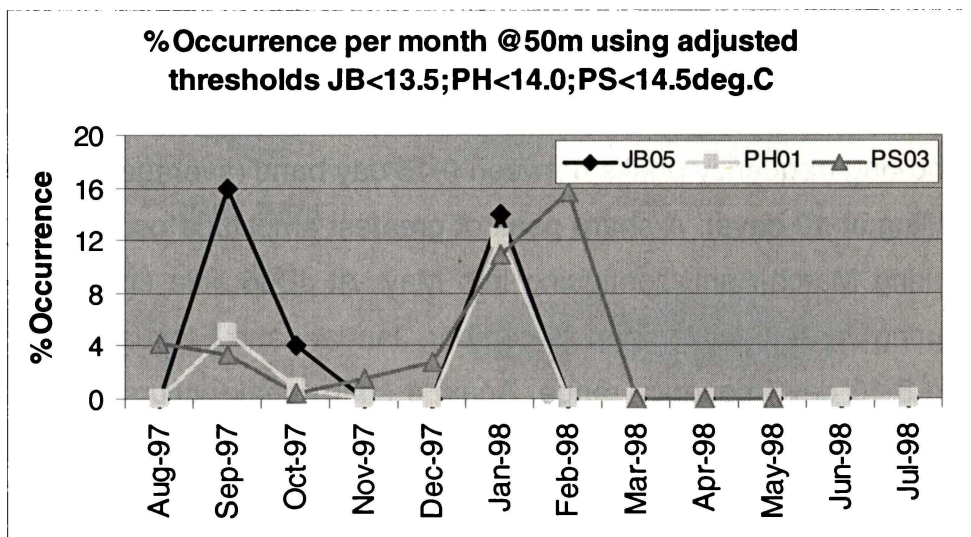


Figure 5: Alongshore frequency of upwelling during 1997-98 from mooring records adjusted for southward slope-water cooling trend.

Regional differences are apparent with further investigation of the expected bimodal spring and summer pattern, exhibiting an increasing southward frequency for the spring event, and a northward strengthening of intrusions in summer. Duration of temperature intrusions was estimated for selected moorings based on the adjusted temperature criteria, using the threshold method outlined in the methods section. Temperature intrusion durations, (defined as 'events') obtained at the three regional sites at a depth of 50m, were typically ranging between 70-100 hours at Port Stephens during January and February, corresponding to 3-4 days in length. Port Hacking had three events in January, ranging between 18-61 hours in duration (0.75-2.5 days). Jervis Bay data demonstrated an event in September that lasted approximately 4.5 days, together with events in January averaging 2.3 days.

Figure 6 displays compressed plots of the power spectrum, calculated from the time series temperature data measured at each of the selected mooring sites. At PS02, we see that little periodic activity is evident between June to September, together with peak frequencies generally occurring between 8-10 days in the other months. Alternatively, PH01 displays bimodal frequency behaviour during June-September, with peaks coinciding with 6-7 days and approximately 15 days frequency. October and November displayed minimal activity, with December to January showing frequency peaks between 9-15 day band (average value probably falling at 10 days). A sharp peak of greatest amplitude occurs at 8-9 days during March-April, continuing into May. At JB05 little activity is evident during June to November. December, January and February demonstrate an 8-10 day frequency range. Again a sharp peak occurs in March-April, bimodal in shape with peaks at approximately 7 and 10 days. The 7-day peak is carried into April-May. In summary, most of the energy falls between the 7-10 day band, however this information in isolation doesn't distinguish variation in peak frequencies, apart from the evidence in seasonal change consistent at all locations demonstrating the minimal peak energy activity between June-September.

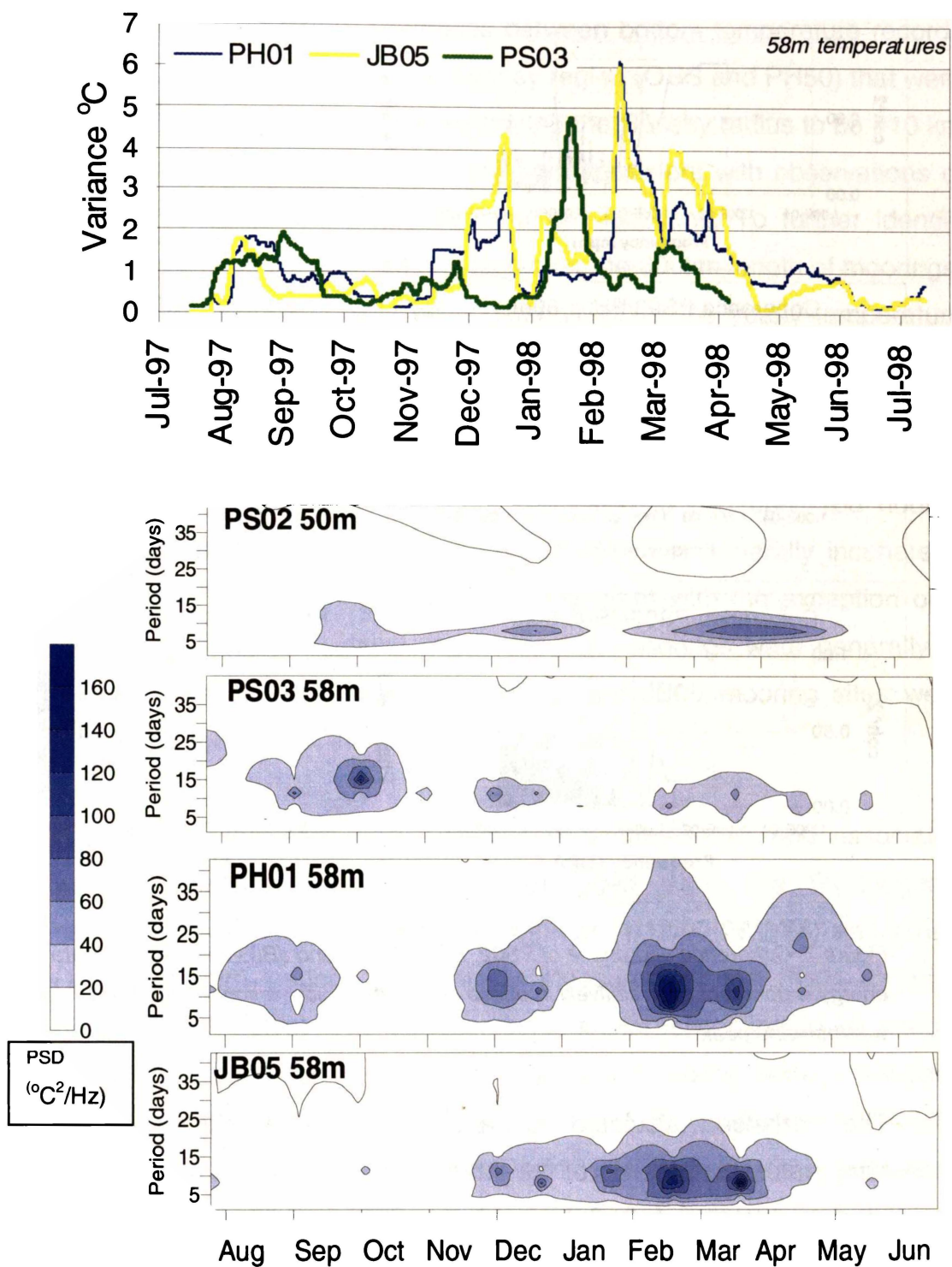


Figure 6: (top) Variance at PS03, PH01 and JB05 during 1997-98 using a 20 day window for bottom water thermistors (58m in 60m water).and (bottom) compressed power spectra plots (DegC^2/Hz) for 50m depth at PS02, and 58m depth for PS03, PH01 and JB01.

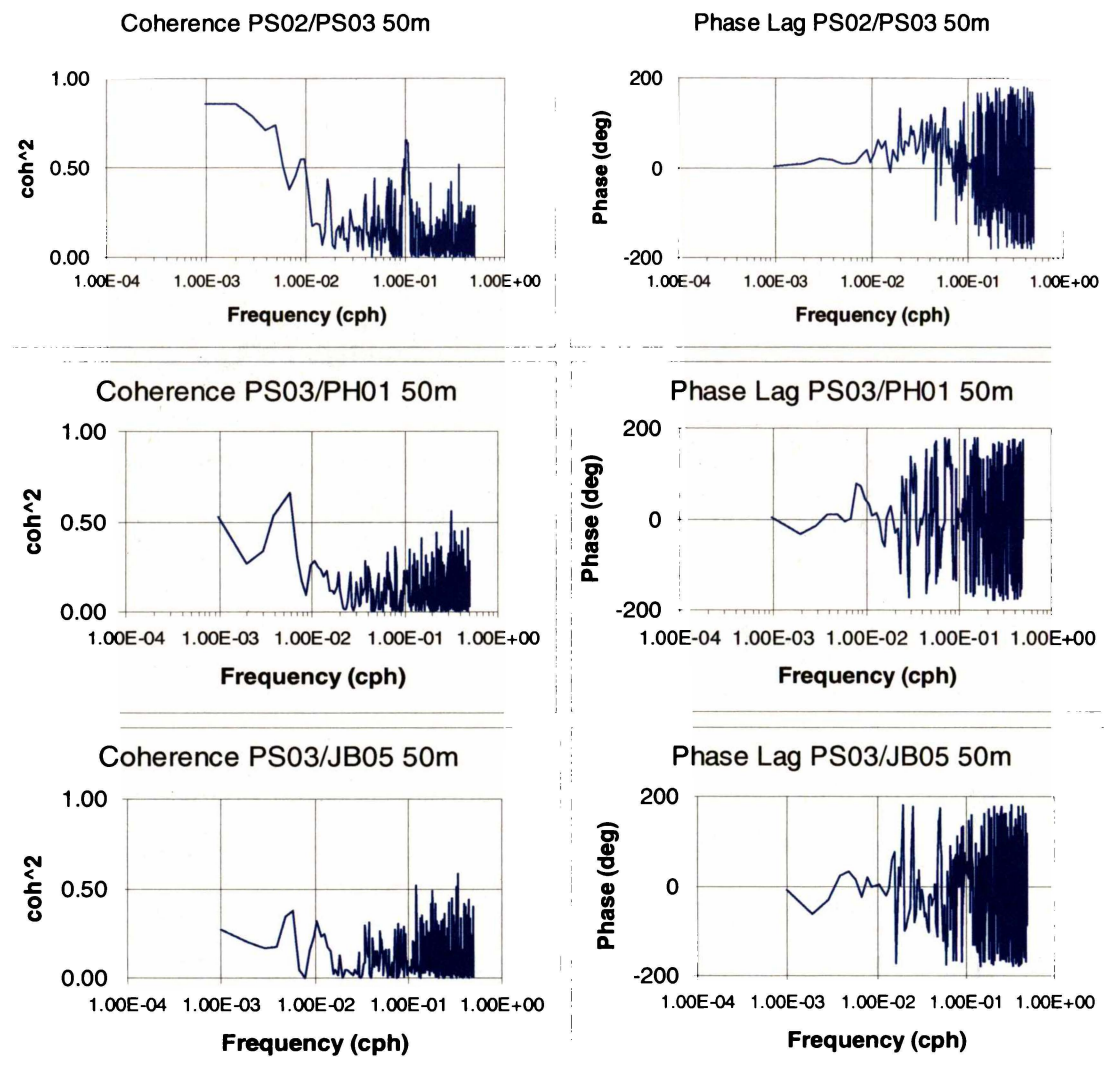


Figure 7: Coherence and phase of PS02, PS03, PH01 and JB05 moorings indicate energy is coherent and relatively in phase across the study region for dominant 7-10 day weatherband peak.

The variance calculated for a 20-day window shifted through the temperature time series of the three regional sites at a depth of 50 m are displayed in Figure 6. Coherent increased variability occurs between the months of December to April at Jervis Bay and Port Hacking with variance peaks of up to 6 Celsius degrees, possibly due to the influence of the EAC behaviour. During this period though Port Stephens demonstrates inconsistent response to the major events with variances of ~4 Celsius degrees greater or less than those at Jervis Bay and Port Hacking. These results emphasise the seasonal and spatial differences in the temperature records.

Lee et al (2001a) found differences between bottom temperature records from inner-shelf moorings in the Sydney region (ORS and PH50) that were only spaced some 25 km. They estimated the Rossby radius to be ~ 10 km for this section of coastline, and this was consistent with observations of divergent flow occurring between the two locations. To further identify spatial differences and assess for lags over the 300km length of moorings, coherence and phase plots were determined for the yearly temperature data between mooring sites. Calculations of phase based on yearly temperature data demonstrated in Figure 7 indicated that the mooring locations PH01 and JB05 were in phase and significantly coherent between $1e^{-3}$ cph -cycles per hour (42 days) to $6e^{-3}$ cph (166 hours). Above this in the higher frequencies, values were generally incoherent. PH01 and PS02 mooring sites were incoherent with the exception of a peak at $5e^{-3}$ cph (8.3 days). Again the two moorings were generally in phase up to $8e^{-3}$ cph (5.2 days). PS02 and JB05 mooring sites were incoherent throughout the frequency spectrum.

Figures 8(a) and 8(b) display temperature time-series and associated wavelet coefficient contour plots calculated using the Biorthogonal continuous wavelet (2:32:2048) for summer (1/12/97-28/2/98) and winter (1/6/98-31/8/98) periods respectively measured at the PH01 mooring (thermistor at 50 m). The summer contour plot is dominated by feature intrusions repeatedly occurring throughout the period with a temporal duration of 15-20days. The winter contour plot demonstrates little activity during the June and July 1998 period, with short intrusion events commencing in August 1998, with typical duration of 8-10days. In order to compare the magnitudes and scales of the two seasonal periods, wavelet variance was calculated.

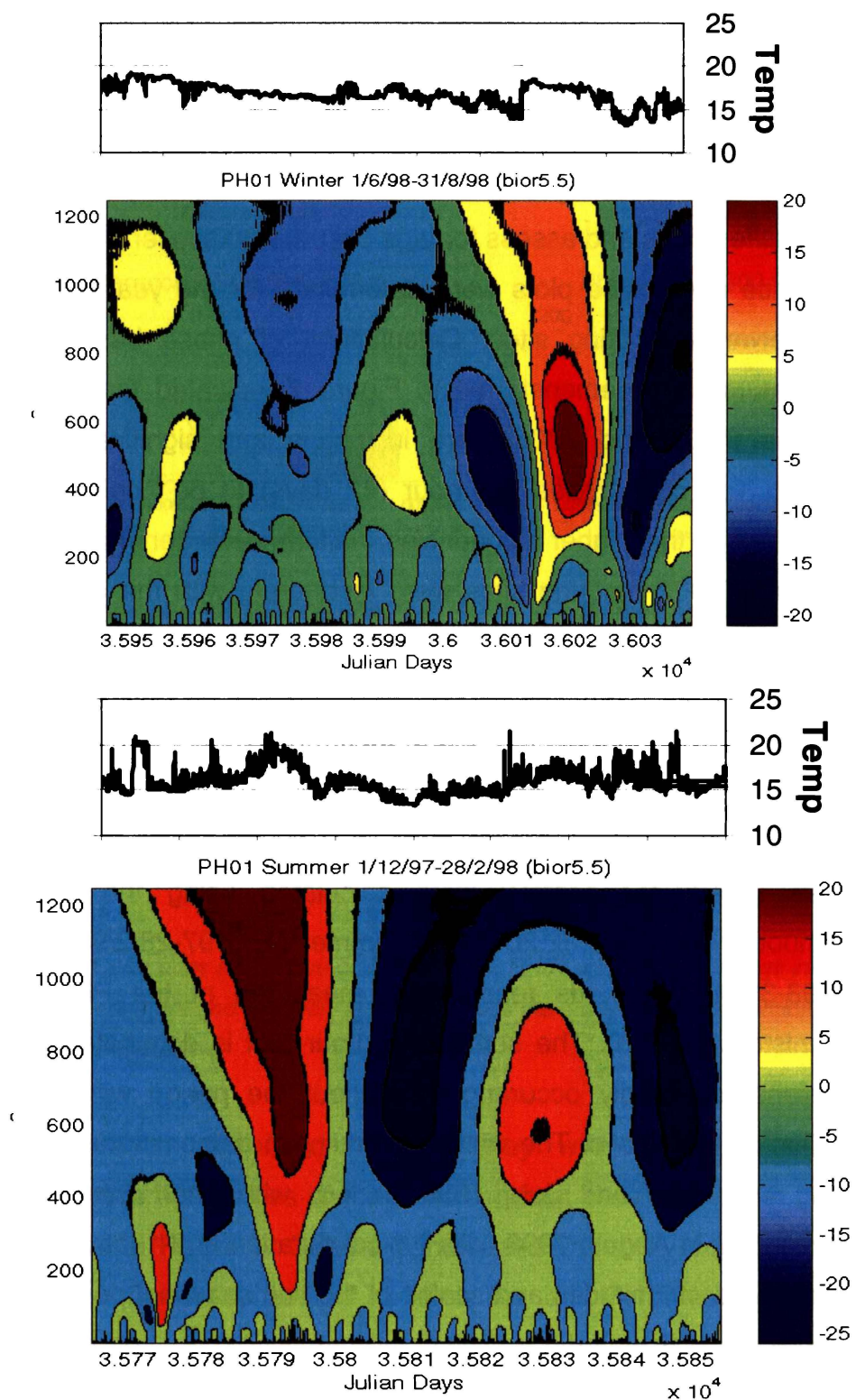


Figure 8: Wavelet scaling at PH01 mooring for (a) winter and, (b) summer seasons, indicate winter is dominated by gradual cooling, whereas in summer upwelling features for 15-20 days dominate.

The wavelet scalogram is an energy spectrum obtained by integrating the square of the wavelet coefficients:

$$W^2(a) = \frac{1}{L} \int_0^L W^2(a, b) db$$

The wavelet scalogram, calculated from the wavelet variance, can be interpreted in terms of energy distribution along the scales a , and thus the scales corresponding to peaks in the scalogram must contribute most to energy. Figure 9 displays the wavelet scalogram calculated from the respective seasonal wavelet coefficients. It is apparent in this figure that the summer season contains more than double the energy of the winter period. The peak summer scale occurs at $a=642$ as compared to the peak winter scale of $a=546$, indicating a longer feature duration of temperature during the summer months.

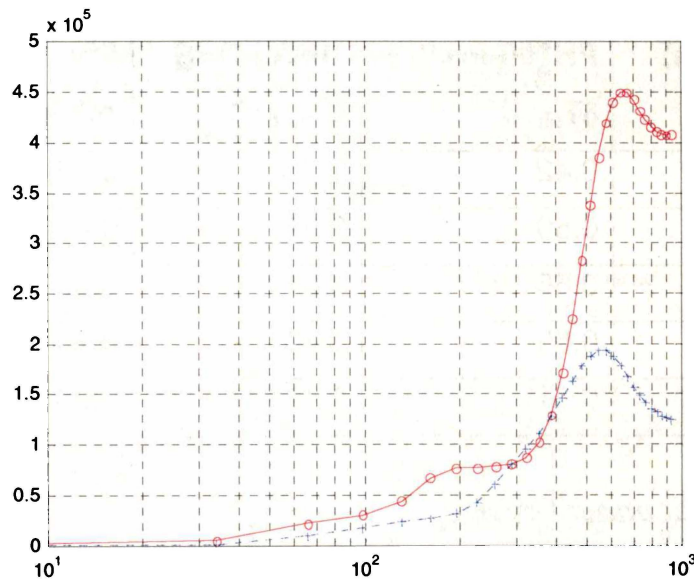


Figure 9: Wavelet scalogram integrates wavelet scales for the two seasons indicating summer (red) has more than double the energy of the winter signal.

Spatial Modelling

As the spatial coverage of the mooring array somewhat limits interpretations of alongshore features, a five year empirical modelling dataset of the region from Ridgeway and Dunn (1998) (as referred to in the data section) provides an opportunity to assess alongshore variability in the region.

Calibration

To instil confidence in the model data, calibrations were carried out for a profile of model elements on the 125 m contour off Sydney (Bondi), and compared with a similar 5-year record from the ORS thermistors (at depths compatible with the model levels) in Table 1 (differences given as $\delta T_{\text{mod}}^{\circ\text{C}}$). Adjustments were made to this calibration error based on expected cross-shelf offsets between the 65 m (ORS) and 125 m (model) profiles by reference to CSIRO Port Hacking 50 and 100 m station data ($\delta T_{\text{ph}}^{\circ\text{C}}$). Lee et al (2001a), suggests there is an average 0.5°C difference between sites at compatible depths. Adjusted model temperatures, are now investigated to assess spatial variance in the temperature record, and in particular identify regions that appear prone to upwelling.

Table 1., indicates the model error after applying the cross-shelf offset.

Depth (m)	PH100-PH50 $\delta T_{\text{ph}}^{\circ\text{C}}$	Model-ORS $\delta T_{\text{mod}}^{\circ\text{C}}$	Resultant Model error $\text{offset } T^{\circ\text{C}} = \delta T_{\text{mod}} - \delta T_{\text{ph}}$
0	0.42	0.71	0.29
10	0.50	0.97	0.47
20	0.65	1.31	0.66
30	0.65	1.40	0.75
50	0.51	1.41	0.90

Looking at annual cycles

Average annual cycles are plotted for the model grid nodes on the 125 m contour at Port Stephens(PS_{mod}), Port Hacking(PH_{mod}) and Jervis Bay(JB_{mod}) Figure 10 represents these as depth slices (0-20 m, 30-50 m, 75-100 m and 100-125 m). The annual cycle at JB_{mod} is coherent throughout the water column, whereas phase shifts and a developed bi-annual signal become apparent in the PS_{mod} and PH_{mod} cycles at greater depths.

From the averaged regional plot, the surface water minimums are in August-September, whereas bottom water minima occur in October and February. These match observations from the CSIRO Port Hacking Stations PH50 in Figure 2. Reference to nutrient cycles from PH50 in Figure 2, suggest that regionally peak bottom water nutrients would occur in February, whilst peak surface water nutrients occur in August-September, accounting for the two main algal bloom seasons observed in the region.

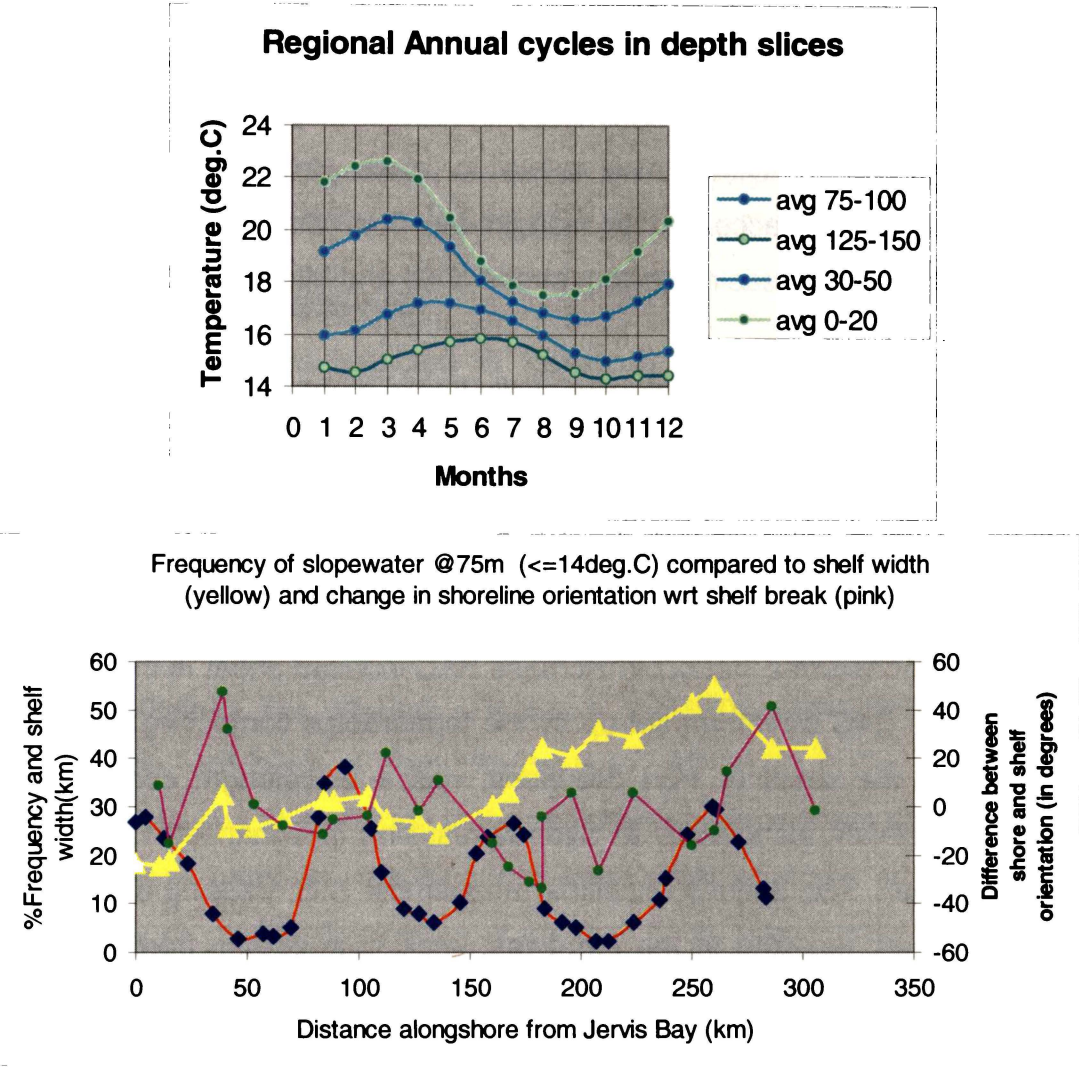


Figure 10: Empirical modelling results show (top) annual cycles are in step with long-term records and coherent across the study region. (bottom) Alongshore modelled upwelling frequency is related to downstream (southward) effects of changes in shoreline orientation and local reductions in shelf width.

Alongshore variance

Figure 10 also relates the alongshore frequency of $\leq 14^{\circ}\text{C}$ temperatures at 75m depth along the 125 m contour between Port Stephens and Jervis Bay, with changes in shoreline orientation and shelf width. Although it has been shown in Figure 4 that slope-water may cool in temperature to the south, the modelling data appears sensitive enough to the $\leq 14^{\circ}\text{C}$ criteria for the purposes of defining regions of peak upwelling. The main upwelling regions are indicated for coastal waters off Newcastle, Broken Bay, Wollongong and Jervis Bay. This increased upwelling frequency is indicated southward (EAC downstream) of major topographic protrusions, with length scales seemingly proportional to the degree of change in frequency. These also relate to shelf width, with a narrowing shelf promoting accelerated alongshore flow that can enhance intrusions through increasing bottom stress (Oke and Middleton, 2001).

Whilst the shelf break essentially tracks alongshore at a bearing of $\sim 20^{\circ}$, it is apparent from this study that regions prone to upwelling are downstream of sharp changes in the shoreline orientation. The prominence of upwelling off Sydney, however, is contrary to this claim. Observations of SST imagery in this region (Lee and Pritchard, 1996) suggest two possible mechanisms that could increase EAC induced shear in the Sydney region. An EAC waveform set-up by the topographic contouring of Stockton Bight to the south of Port Stephens, has a wavelength compatible with the distance alongshore to Sydney resulting in enhanced EAC shear on the shelf. The Sydney coastline runs almost N-S, causing a narrowing of the shelf, resulting in the narrowest shelf downstream from Point Stephens. Stream-flows contouring the shelf-break are often seen impinging the Sydney region. As Oke and Middleton (2001) indicated, enhanced bottom stress from shelf narrowing can drive an onshore bottom boundary layer that supplies the shelf with cooler slope-water. These feature are shown in SST imagery in Figure 11.

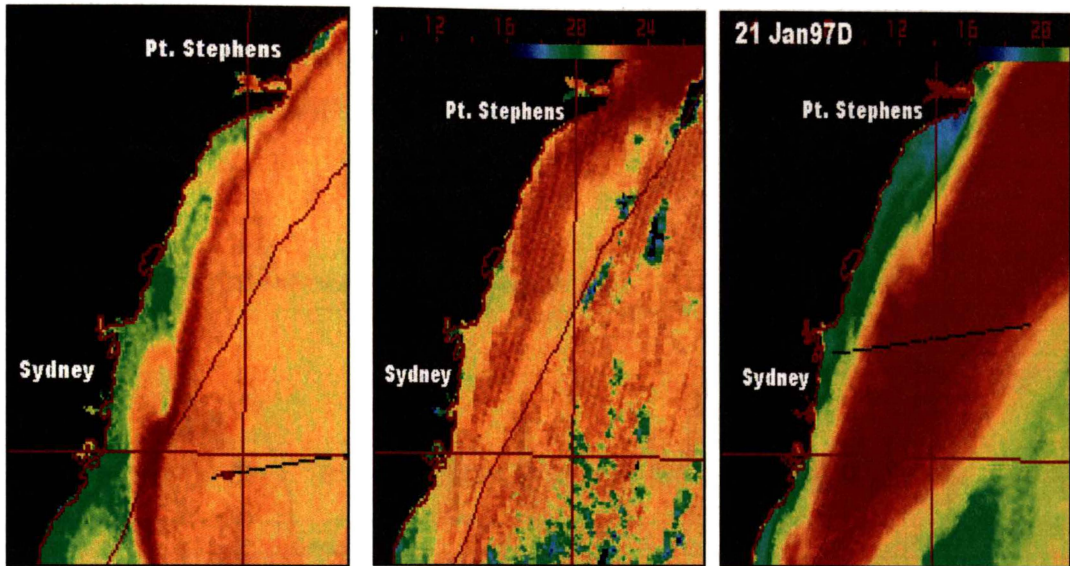


Figure 11: SST imagery during January 1997 shows coastal topography disrupting the EAC streamflow into back-eddies that are advected along the inshore front of the EAC.

The Port Stephens back-eddy

From mooring records depicted in Figure 4, the sharpest rotation of shoreline orientation in the study region occurs over a ~40 km distance between the mooring south (PS03) and north (PS02) of Point Stephens. Distributions in Figure 4 indicate the second warmer peak (~ 21°C) that appears in the PS02 record, becomes the dominant peak by the PS03 mooring, at the expense of the cooler 15-16°C peak. Topographically this area also depicts the greatest change in coastline orientation (~50°), running from ~10° north of Point Stephens to ~60° south of the point. As Figure 10 indicates, this change in the coastline however is not reflected in the shelf break contours, resulting in a shelf widening south of the point and thereby promoting divergence of on-shelf flows. Observations of SST imagery in Figure 11 indicates how this can have a marked effect on the stream-flow of the EAC, with a back-eddy forming in the lee of Point Stephens. A 4-month record from a bottom mounted S4P current meter located in this area at the PS03 site during November 1996 to February 1997 is used here in conjunction with SST imagery to examine the back-eddy activity.

Whilst the majority of this record has variable flows that are generally $<0.1 \text{ ms}^{-1}$, the strongest flows (up to 0.4 ms^{-1}) occurred in January 1997

associated with back-eddy activity. Figure 12 plots the bottom temperature and current vectors for this period, and accompanies the SST imagery shown in Figure 11. From this information the following synopsis has been formed.

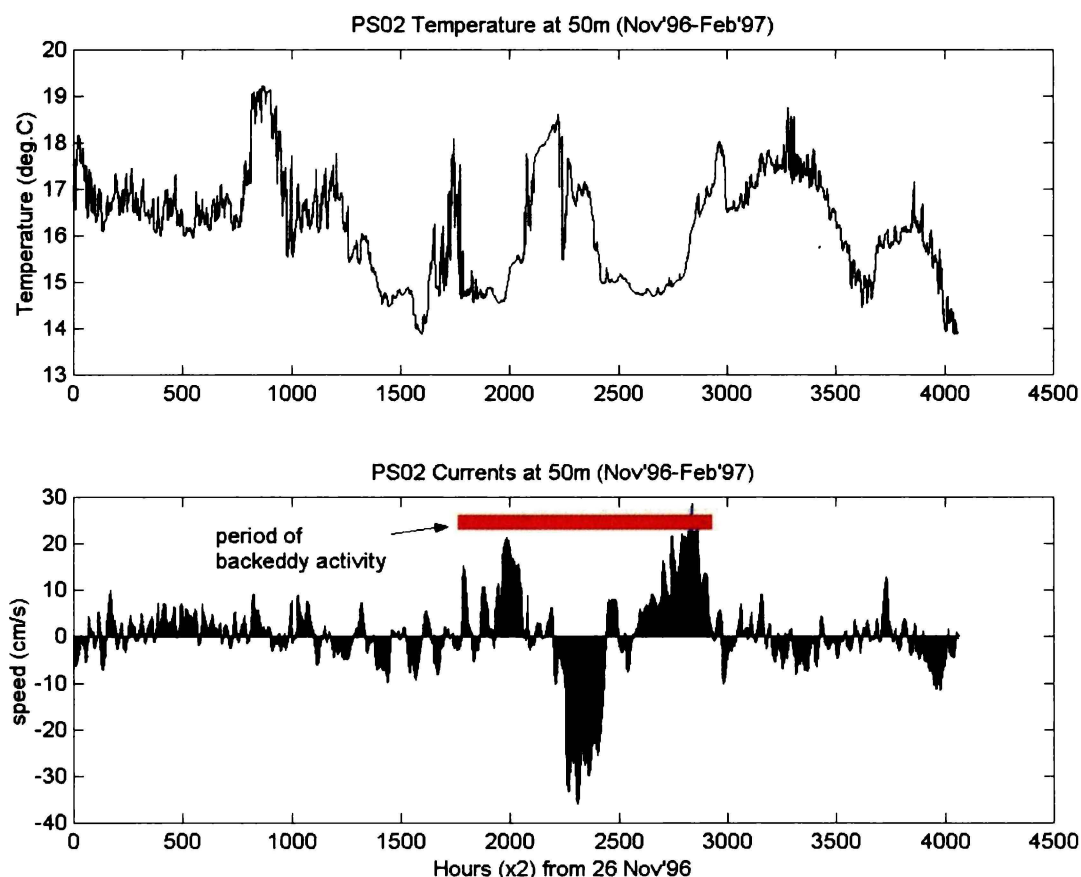


Figure 12: S4 current mooring off Port Stephens in Nov'96-Feb'97, indicates peak activity associated with back-eddy formation in January '97 occurring over 10 day intervals, as seen in accompanying SST thumbnails.

The S4 record associates the initial back-eddy sitting in the lee of Point Stephens in early January 1997 as positive alongshore (northward) flows of 15°C cool water at 0.2 ms^{-1} . With the approach of the EAC meander, warm 18°C EAC is associated with enhanced negative (southward) flows of 0.35 ms^{-1} . As the EAC retracts offshore the bottom water cools, and flow rotates to the north again accompanied by a cooler 15°C signal. By late January 1997 this eddy has spun-out and background flows of $<0.1\text{ ms}^{-1}$ re-establish. The formation and dispersion of the back-eddy during this period occurred over a period of ~ 10 days.

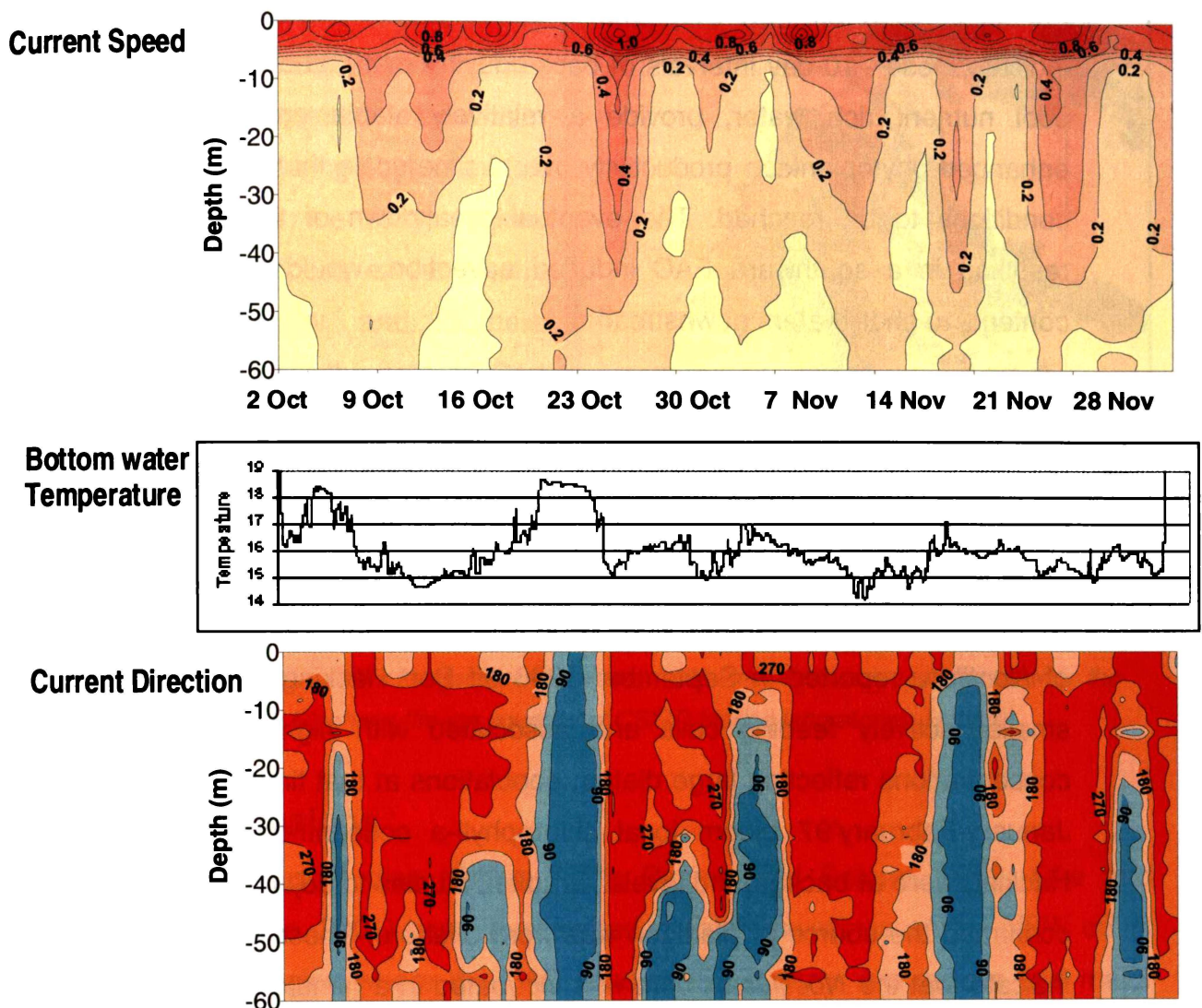


Figure 13: ADCP data at the PS03 location in Oct-Dec'97 confirms back-eddy formations oscillating over 10-15 days.

The Oct-Dec'97 ADCP mooring in Figure 13, indicated similar back-eddy formations oscillating at 10-15 days intervals, matching bottom temperature records and SST observations. The ADCP record however provided insight to how a depth profile responds to eddy evolution. Data indicate a phase lag of ~5 days before the NE jet initiated in the bottom 20 m spreads to throughout the water column bringing with it peak bottom temperatures. Whilst the back-eddy feature is apparent throughout the water column, peak current strengths ($\sim 0.2\text{--}0.5 \text{ ms}^{-1}$) are also more uniformly spread, whereas during the SW pulses of EAC advected flows, strengths of up to 1 m/s are confined to the upper 10 m.

Temperature-nutrient relationships obtained from four cross-shelf transects taken off Port Stephens in January 1997 (Lee et al, 2002), indicate these ~10-day intervals of back-eddy that bathe the shelf with cool nutrient rich water, provide a relatively stable environment for enhanced phytoplankton productivity over a time scale that allows bloom conditions to be reached. The eventual breakdown of the back-eddy resulting in a southward EAC induced advection, would distribute the contents to shelf-waters downstream.

Observations were made Murray and Suthers (1999) on plankton populations of *Noctiluca scintillans* at both Port Hacking and Port Stephens during the 1996-97 summer period. Coincident sampling found blooms of small actively feeding/reproducing cells in the Port Stephens region, whereas off Sydney the cells were large and senescent. An earlier bloom of *Noctiluca* reported in September 1996 off Port Hacking, had typically smaller actively feeding cells and associated with high chlorophyll-a concentrations reflecting large diatom populations at that time. During the January-February'97 bloom local chlorophyll-a concentrations off Port Hacking were at background levels. Gradient studies to adjacent estuaries confirmed the source of plankton was from offshore. These observations indicate that the *Noctiluca* bloom was incubated in a remote region to the north and was most likely entrained by the southward flowing EAC. The SST imagery, S4 current data and supporting CTD/WQ transects indicate that an appropriate physico-chemical environment existed within the back-eddy in the lee of Point Stephens.

SeaWiFS imagery assessed by Lee et al, (2001b) during the following summer in January 1998, identified the presence of this back-eddy as a strong chlorophyll response to eddy enrichment (Figure 14). The period of eddy formation observed in the satellite imagery was associated with the strong variance signal observed at the local temperature mooring (PS03) in Figure 6 during January 1998. This peak was incoherent with low signals detected elsewhere in the array, suggesting enhanced localised dynamics of the type observed in the 1996/97 mooring records. The

imagery also indicates an associated southward streaming of the plankton alongshore from this retention cell, identifying this as an important mechanism for enhancing phytoplankton levels in the study region. This supports earlier claims by Murray and Suthers (1999) that the area off Port Stephens is an important controller for phytoplankton population configuration to the south.

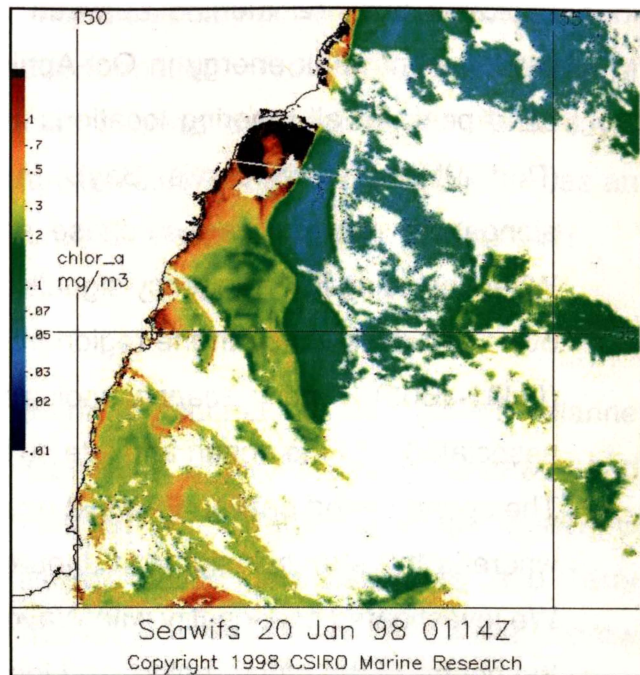


Figure 14: SeaWiFs imagery for 20 January 1998, indicates back-eddy formation in the lee of Port Stephens (Image courtesy of CSIRO Marine laboratories, Hobart).

Conclusions

Numerous studies (Grant, 1971; Pearce and Boland, 1982; Oke and Middleton, 2001) have investigated coastal upwellings on the NSW coast in the region where the EAC consistently streams alongshore and major bathymetric discontinuities set up predictable upwelling cells in their lee (e.g. Laurieton). The coastal region south of the main East Australian Current separation zone ($\sim 32^{\circ}\text{S}$) poses a more difficult problem in locating and quantifying upwellings due to the episodic nature of shelf encroachments by a turbulent EAC eddy field. Long-term data collected off Sydney have previously guided assessments of nutrient enrichments within the region. Initial comparisons with a 4-month mooring off Port Stephens, and the ORS off Sydney in 1996/97, indicated coherence for signals >5 days although phase was often variable. Transect data during 1995-97 from Port Stephens, Port Hacking and Jervis Bay also highlighted regional differences suggesting temperature-nutrient relations were biased by a southward cooling trend.

Despite these inferred regional differences, the temperature moorings deployed over 12 months between July 1997-July 1998 indicated the predominant peak energy in Oct-April occurred at the 7-10 day weather-band peak for all mooring locations in a 300km alongshore study region (Port Stephens to Jervis Bay). In the weather-band period, these alongshore records were in-phase and coherent for across the region. When including low frequency signals associated with the EAC, coherence over 7-42 days varied in the region from 40 km (PS02 & PS03) to 150 km (PH01-JB05). The variance indicated two distinct dynamic periods associated with the spring and late summer plankton blooms in the region. The spring period between August and October was coherent alongshore, whereas the stronger signal in January-March indicated regional effects. We investigated seasonality with Wavelet analysis on the PH01 mooring in the centre of the study region, and identified gradual cooling in winter and upwellings at scales of 15-20 days in summer as the dominant modes.

The upwelling frequency (after prescribed cooling adjustments to the threshold) at thermistor mooring locations alongshore, was up to 16% for coherent spring and summer peaks occurring in the months of September, January and February. Average upwelling frequencies ($\leq 14^{\circ}\text{C}$ threshold) for all moorings alongshore, indicated perturbations of 50-100 km at the coastal 50 m moorings in the Jervis Bay to Port Hacking section. Poor coverage between Port Hacking and Port Stephens (due to mooring loss), limited a complete unbiased comparison of alongshore frequencies. Further assessment of the alongshore variability was performed with calibrated regional model results, relating frequency of cool water intrusions to topographic factors such as shelf width and change in shoreline orientation. The modelled alongshore upwelling variability occurred at scales of ~ 100 km, which were compatible with indications from the more sparsely located mooring data. Topographic interaction with alongshore flow appeared as an important factor in generating localised uplifting, with clear increases in upwelling frequency southward (EAC downstream) of major changes in shoreline orientation. The two dominant bathymetric features occur at Port Stephens and Jervis Bay, where

changes of 50° between shelf and shoreline are evident. A focus on the feature south of Port Stephens, indicated dominant energy associated cool water intrusions during back-eddy formation. From some six months of current mooring data, back-eddies evolved over periods of 10-15 days, and through companion phytoplankton studies have been implicated as an important upstream plankton source for the coastal region to the south.

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4-3 CHAPTER CONCLUSIONS

The information within this chapter paper defines the oceanic nutrient intrusion patterns affecting coastal waters in the Australian study region and thereby, in combination with the preceding chapter, completes the first thesis objective. The temporal signals dominated by the strong seasonal signal, provides a simple predictor for the temporal distribution of intrusions. A strong relation of forcing patterns and coastal/shelf topography emerged as the principle factor for the spatial distribution of the seasonal intrusions. These spatial scales ranged from topographic interruptions of alongshore geostrophic flows, to seasonal and inter-annual pulses. With these spatial and temporal scales defined, the following chapter focuses on quantifying the nutrient and phytoplankton patterns occurring within a nutrient intrusion event at key topographic flow control points identified in this chapter.

Chapter 5: Oceanic Nutrients

5-1 CONTEXT OF PAPERS WITHIN THE THESIS

The temporal and spatial scales of intrusion processes affecting coastal waters in the Australian study region, have been defined in the previous chapter. Scenarios of these enrichment events now require assessment to complete the thesis objective of defining the oceanic influence on coastal water patterns. Repetitive sampling transects were triggered by the identification of coastal upwelling scenarios from real-time ocean monitoring. Key upwelling locations defined in the previous chapter were the focus of these sampling campaigns. Combining results from these investigations with supporting long-term records within the study program, these scenarios were investigated in the following paper. Cross-shelf transects covered the full shore to shelf break extent to enable a full account of cross-shelf fluxes, and were maintained to capture the phytoplankton response. Within each scenario the driving mechanisms are identified and the associated nutrient components quantified. The examples of algal response to the upwelling scenarios outlined in this paper, provides an introduction to the more specific studies on phytoplankton response in the following chapter.

The paper in this chapter was presented at the Plankton Symposium, Portugal, 2001, and is to be submitted to the Journal of Marine and Freshwater research.

5-2 THE INFLUENCE OF WESTERN BOUNDARY CURRENTS OFF THE EAST COAST OF AUSTRALIA ON PHYTOPLANKTON DYNAMICS IN THE COASTAL ZONE

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Keywords: upwelling, East Australian Current, Noctiluca, nutrients

Abstract

Phytoplankton blooms are often studied too late in their development when the surface expression of predominantly senescent cells triggers an investigation. As a result studies typically depict an environment exhausted of nutrients and provide limited information on the mechanisms that caused the bloom. The purpose of the study reported here is to quantify the oceanographic and meteorological conditions leading to nutrient enrichment and subsequent phytoplankton responses (blooms) through a series of cross-shelf transects undertaken over spring/summer seasons in 1990's along Australia's east-coast. The region is impacted by western boundary current encroachments of the East Australian Current (EAC), and anthropogenic inputs from the Newcastle-Sydney-Wollongong conurbation. Synoptically triggered responsive sampling transects along a 300km section of the shelf, identified coherent diatom - dinoflagellate successions over several weeks after oceanic nutrient enrichment of shelf waters. Concurrent physical observations identified perturbations of the East Australian Current into meanders, eddies and back-eddies by coastal and shelf topography as a key influence in determining the local nutrient budget and phytoplankton distributions. Response of the heterotrophic dinoflagellate *Noctiluca scintillans* (Macartney) occurred after sufficient critical prey mass of diatoms was achieved, and overwhelmed zooplankton communities. The extent and duration of these blooms were unprecedented in these coastal waters, and were mitigated by local prevailing circulation patterns.

Background

Changes in the orientation of the coastline and in local bathymetry can steer western boundary currents to locally enhance cross-shelf transports, which can lead to instabilities and local upwelling similar to that described for the Agulhas Current by Gill and Schumann (1979). Topographically driven instabilities on the inshore edge of the Gulf Stream are frequently observed to cause localised nutrient enrichments in coastal waters. Tee and Smith (1993) identified a topographically driven upwelling system off Cape Sable in south-western Nova Scotia where bottom topography

variations induced an uplifting of slope-waters which were subsequently advected alongshore by a prevailing coastal current. This system allowed the upwelled nutrients to be supplied to coastal waters downstream of the upwelling zone.

Various investigations along Australia's east coast have identified shelf intrusions of cool nutrient rich waters that originate from the shelf slope (Cresswell, 1994; Tranter et al, 1986; Rochford 1984) associated with the regional western boundary current, the East Australian Current (EAC). These slope-water intrusions have commonly been delineated by temperature-nutrient relations, and at times, by an arbitrary temperature of $\leq 14^{\circ}\text{C}$ (Cresswell, 1994). These waters typically have low salinity ($<35.2\text{‰}$) and high nitrate concentration ($>70\text{--}100\text{ }\mu\text{g.L}^{-1}$). Early work by Humphrey (1960, 1963) suggests that they also have a high phosphate concentration ($>20\text{ }\mu\text{g.L}^{-1}$) and low pH (≤ 8.15). In contrast, EAC waters that often dominate surface mixed layer on the NSW shelf originate from the Coral Sea are warm and oligotrophic.

Tranter et al. (1986) indicated that intrusions of this slope-water occurred frequently but irregularly from August to April based on data from 28 years of monitoring at a station located off Port Hacking (near Sydney) in about 100m of water. Hallegraeff and Reid (1986) indicated two distinct periods of enhanced phytoplankton activity that related to surface layer nutrient maxima in the austral spring (September-October) and bottom layer nutrient maxima in late summer (February-March). The austral spring experiences predictable diatom blooms that coincide with re-stratification of the homogenous winter water column. The conditions for the austral summer are more indicative of bottom layer intrusions of slope-water, and may relate to regional patterns of the EAC's geostrophic forcing.

Similar to observations by Tee and Smith (1993) off Nova Scotia, Cresswell (1994) has suggested EAC upwellings could be advected as a plume by ambient shore parallel flows and, since there may be a lag of 1-2 weeks between nutrient enrichment events and peak levels of plankton

nitrogen (Newell, 1966), blooms may occur at locations well removed from the site of upwelling. Recent modelling studies by Gibbs et al (1997) proposes that the distortion of local shelf bathymetry due to the protrusion of Jervis Bay, some 150km to the south of Sydney on Australia's east coast, predisposes this location to slope water intrusions. Spectacular blooms have occurred in Jervis Bay in recent times, most notably a unique *Gephyrocapsa oceanica* bloom, which dominated the bay for many weeks during the summer of 1992-1993 (Blackburn and Cresswell, 1993).

Griffin and Middleton (1992) and Gibbs et al (1997) proposed, by modelling simulations, that a long duration of northerly, upwelling favourable winds was critical in driving slope water intrusions into the bay. Gibbs et al (1997) suggested that, under steady EAC conditions, the upwelling favourable bottom boundary layer ('Ekman pumping') is rapidly shut down in the absence of wind-forced upwelling. Oke and Middleton (2001) modelled the region 150 km to north of Sydney (around Port Stephens) and identified a greater role for EAC instabilities driving upwellings. In this region they suggest instabilities are formed by a combination of shelf narrowing and significant changes in shoreline orientation. As the shelf narrowed, bottom friction associated with the acceleration of southward EAC flows simulated a shoreward advection of slope-water within a bottom boundary layer. Further downstream an eddy which entrained these slope-waters was generated in the lee of the major change in the orientation of the shoreline. However, neither of these modelling studies were validated and few data points were available to describe phytoplankton responses to these physical phenomena.

Long-term coastal investigations by CSIRO have continued at two stations offshore from Port Hacking (50 m and 100 m station), New South Wales, since the 1940's (Middleton et al 1996, Hahn et al 1977). Studies at these stations have included variations in plankton pigments (Humphrey 1960, 1963, Hallegraeff 1981), water quality parameters (Newell 1966) and their relationship with phytoplankton numbers (Grant and Kerr 1970, Grant 1971, Hallegraeff 1993), and the seasonal succession of phytoplankton in

relation to the hydrological environment (Jeffrey and Carpenter 1974, Hallegraeff and Reid 1986).

When present in excessive amounts nutrients may cause enhanced phytoplankton growth (including nuisance blooms and/or toxic algal species) or a change in the composition of phytoplankton and other species. Various studies around the world have demonstrated a direct link between increasing eutrophication and/or shifts in nutrient ratios with respect to phytoplankton composition and abundance (Oviatt et al 1989; Graneli and Moreira, 1990; Reigman et al 1992). In addition, both laboratory and coastal marine mesocosm experiments have demonstrated that different taxonomic groups of phytoplankton may respond to environmental variables in very different ways eg. diatoms have high growth rates under nutrient rich-conditions (Graneli and Moriera, 1990) while monads and flagellates do not (Oviatt et al 1989).

The large heterotrophic dinoflagellate *Noctiluca scintillans* is the most common 'red tide' organism in New South Wales coastal waters at present. Although this species was first identified in 1933 (Dakin, 1973), Hallegraeff (1995) indicates that the first visible bloom of *Noctiluca* was recorded in August 1992. Since then *Noctiluca* blooms appear to have increased in frequency and intensity, with numerous events being reported to local authorities (Ajani et al, 2001a). Interest in this species has intensified as many researchers have suggested a link between increased abundance and increased nutrient enrichment (Porumb 1992; Ya and Xin, 1993) and similarly an increase in bloom frequency in areas with a history of anthropogenic input (Lam and Ho, 1989; Hodgkiss and Yim, 1995; Adnan 1989; Ya and Xin, 1993; Qi et al, 1993).

Ajani et al (2001b) suggests, that in NSW coastal waters, short-term diatom blooms may provide the link between episodic slope water intrusions (typical of late summer) and the occurrence of *Noctiluca* blooms. *Noctiluca* may prey on short lived diatoms blooms and quickly increase in abundance. When nutrients become eventually limited and the short-term

diatom bloom ceases, *Noctiluca* growth and reproduction may become inhibited resulting in final aggregations of senescent *Noctiluca* cells represented as a visible bloom.

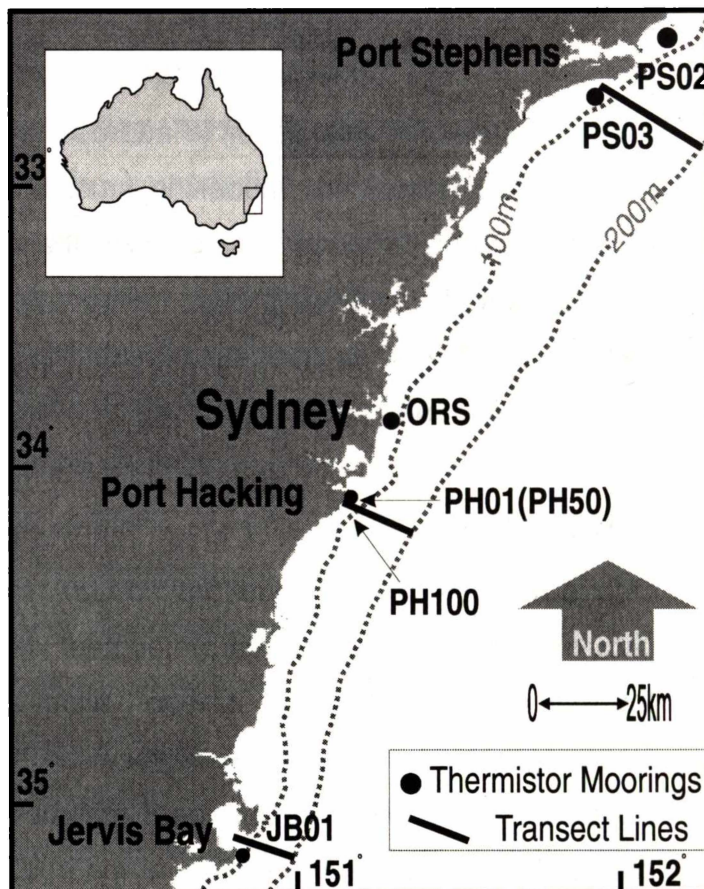
It is the subject of this paper to address the upwelling mechanisms that have been proposed in modelling studies and validate their impact on phytoplankton patterns (such as these diatom – dinoflagellate successions) by assessing shelf transect data collected during upwelling periods off the east Australian coast, in conjunction with companion moored time series data.

Methods

During the 1995-1997 study campaign, weekly surveillance of ocean circulation patterns favourable for coastal upwelling was undertaken using thermal satellite imagery. Images were obtained from the National Oceanographic and Atmospheric Administration (NOAA) series of Advanced Very High Resolution Radiometer (AVHRR) satellites which sense the visible, near infrared and three thermal infrared wavelength bands. Data were collected and processed by the CSIRO Marine Laboratories for sea surface temperature (SST) using a combination of two of the thermal infrared bands. This produces ~1 km pixel SST maps accurate to 0.1°C. The SST images were interpreted on the basis that warmer water is dynamically higher than cooler water thus promoting movement down thermal gradients with Coriolis effects deflecting the flow to the left.

To monitor and assess slopewater intrusions, bottom layer current and temperature data were collected by moored Interocean S4 current meters located in coastal waters off Sydney (ORS) and Port Stephens (PS03), as shown in Figure 1.

Figure 1: Locality map showing the three transects, and instrument moorings, used in the investigation along a 300km alongshore stretch of the east Australian seaboard.



Instruments at both locations are calibrated to measure currents (accuracy 0.01m.s^{-1}), temperature (0.02°C) and depth (0.15%). Monitoring at the Ocean Reference Station (ORS) in 65m water depth $\sim 3\text{km}$ off Bondi, provided quality controlled current and temperature data in the depth profile as hourly data from 5 minute sampling averages. S4 Current meters were located at 17m and 52m, wind was recorded by an RM Young anemometer located 5m ASL on the buoy, and temperature data was recorded by 16 Aanderaa thermistors strung from below the buoy to the 52m current meter. This facility, operated by Sydney Water, has been in operation since July 1989 (Lawson and Treloar, 1993). For the purpose of this study, the S4 meter at Port Stephens (PS03) was deployed between 26 November'96 and 20 February'97 at 59m in 61m water off Boat Harbour ($32^{\circ} 50.60'\text{S}$, $152^{\circ} 04.73'\text{E}$), recording 5 min averages every 30 mins.

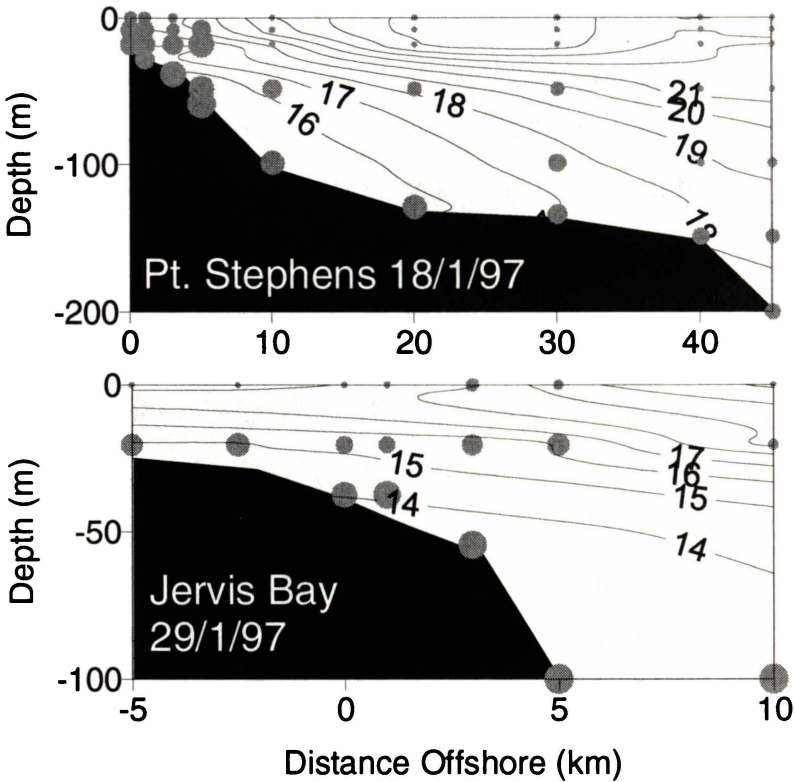
A total of twenty four shore-normal transects were undertaken for the three transect lines at Port Stephens (PS - 45km), Port Hacking (PH - 25km) and Jervis Bay (JB - 15km) as shown in Figure 1. These transects were undertaken in austral spring/summer seasons of 1995/96 and 1996/97, and extended to the shelf-break (200m) at nine, eight and six sampling stations respectively along the PS, PH and JB transect lines. A sampling transect typically consisted of instrumental probe profiles, water quality sampling, and algal net hauls. The twenty-four transects combine data from a routine sampling program undertaken during this period, and focussed repetitive sampling at PS and JB transects during the 1996/97 season.

The template for these stations was designed according to the across-shelf scale of the hydrographic features that regionally dominate (Franks, 1995). We utilised the local internal Rossby radius of deformation (R_i) to provide a scale curvature for coastal currents driven by pressure gradients, wind and topography. For the range of latitudes (31-35°S) spanned in this study, $R_i \sim 10\text{km}$. Therefore to resolve coastal current features of $\sim 10\text{km}$, generic station spacing was set at 5km. Within 5km of the coast this spacing was reduced to 1, 3 and 5km to help resolve anthropogenic inputs and interactions with coastal topography. This template was applied for the PS and PH transects but required modification for Jervis Bay as its promontory extends $\sim 5\text{km}$ offshore from the alignment of the east Australian coast. The narrow entrance of the embayment causes a residence/flushing time that ranges between 10 and 74 days (24 day average) depending on the external oceanic forcing (Holloway et al, 1992). So to resolve how conditions within the bay would respond to ocean forcing, the sampling transect extended from 5km within the Bay to the shelf-break, and retained higher sampling intervals at the coast, represented by the bay entrance.

As the focus of this paper is on the responsive sampling program during December 1996-March 1997, Figure 2 shows sampling stations along the

Port Stephens and Jarvis Bay transects, and Tables 1 and 2 list their respective sampling schedules.

Figure 2: Temperature during upwelling conditions along the Port Stephens (18 January 1997) and Jarvis Bay (29 Jan 1997) transects and corresponding water quality sampling shown here as oxidised nitrogen results (scaled from 0 - 150µg.L-1)



A SEABIRD SBE25 Sealogger Conductivity, Temperature and Depth probe (CTD) was deployed at stations along the shore-normal transects to profile to within 5m of the seabed. The CTD operated at 8Hz with pumped temperature and conductivity cells that were ducted to ensure a constant response regardless of profiling speed on the downcast. This ensured high accuracies for temperature (0.004°C) and conductivity (0.0003 S.m-1). The CTD was instrument was coupled with a Seatech 25cm pathlength Transmissometer to measure relative turbidity, and a Chelsea Instruments Fluorometer (chlorophyll-a range 0.01-100 µg.L-1 to indicate phytoplankton abundance.

On the eleven transects undertaken in 1995/96, Acoustic Doppler Current Profiles were utilised to measure current profiles concurrently with the CTD sampling. A 300kHz RD Instruments ADCP was employed from the stern of the research vessel and sampled in 1 metre bins from a surface bin of ~4m to a maximum depth of ~160m depending on sea conditions. To reduce transect time the ADCP was operated at each sampling station, rather than run as a continuous shore-normal transect.

Depending on station depth, water samples were obtained using a string of 5-Litre Niskin bottles located at 0.5m(surface), 10m, 20m, 50m, 100m, 200m and 5m from bottom depth. From each Niskin bottle sub-samples were taken for nutrient analyses. Nutrients were analysed using flow injection analysis (APHA, 1998) for oxidised nitrogen (APHA Method 4500 - NO_x I modified; PQL 1 µg.L⁻¹), ammonia (APHA Method 4500 - NH₃ H; PQL 2 µg.L⁻¹), silica (APHA Method 4500 - Si F modified; PQL 5 µg.L⁻¹) and reactive phosphorus (APHA Method 4500 - P G; PQL 1 µg.L⁻¹). Chlorophyll-a (APHA Method 10200 H; PQL <2 µg.L⁻¹) and phytoplankton species density were also determined. Nutrient samples were filtered (0.45µm) within 6 hours of collection and, with exception of silica, frozen at -20°C prior to analysis. Two litre water samples for chlorophyll-a analysis were kept at about 4°C and filtered within 12 hours of collection using a Whatman 0.7µm glass fibre filter under vacuum. Water samples (250 mL) for phytoplankton analysis were collected and preserved immediately with 3% glutaraldehyde and refrigerated.

After each CTD cast, a 20 µm plankton net haul was made for additional algal identification. This was dropped to a depth of 50m or less (depending on the depth of water at each station) and vertically hauled through the water column.

All algal samples were examined with a light microscope (maximum magnification X400). Net haul samples, without any further concentration, were used to document overall taxa present. Water samples (250 mL) were concentrated to 10 mL overnight and refrigerated until chlorophyll results became available. Where chlorophyll concentrations equalled or exceeded 1 µg.L⁻¹ for a particular depth sample, algal enumeration was made by counting to 100 units (corresponding to a statistical error of less than 20%), from this sample using the Lund cell method (Lund et al 1958). Visible algal blooms were sampled using the pole method (Sournia 1978) and cell counts determined using the Lund cell method as above.

Results

The following results are presented in two sections. The first section on regional dynamics defines both seasonally and spatially where upwellings are prevalent in the study region, and identifies a number of mechanisms that are likely to force these shelf intrusions, and methods by which to monitor them. The second section details two upwelling scenarios that were triggered by synoptic monitoring of SST imagery and ORS real-time data, and duly sampled by repetitive transects at key upwelling locations off Port Stephens and Jervis Bay.

The Regional Dynamics

Utilising the $\leq 14^{\circ}\text{C}$ thermal "tag" for slope-water off Sydney (Cresswell, 1984), the 10-year time series of hourly temperature data from the ORS (Nov 1990-Nov' 2000) was processed as weekly averages to identify the frequency of slope-water intrusions in coastal waters for a typical annual cycle. Figure 3 show intrusions occur for up to 10% of the time and are confined to spring/summer seasons (August to March), corresponding to the typical phytoplankton bloom periods observed by Hallegraeff and Reid (1986). During these spring/summer seasons (Oct-March for 95/96 and 96/97) intrusions of cool slope-waters were identified from near-real-time ORS data and SST imagery (example referred to later in Figure 7), and transect sampling programs duly undertaken.

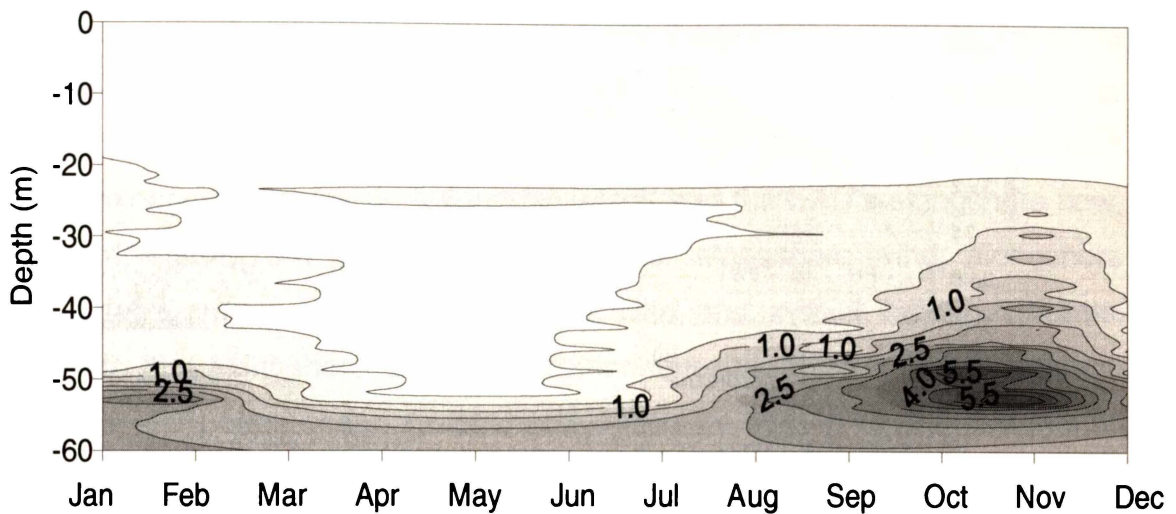


Figure 3: Averaged seasonal cycle at the ORS(1990-2000) represented as a frequency contours (per week) of cool water intrusions (<14°C) from hourly temperature records.

A data summary of the twenty four transects undertaken in this study are provided in Figure 4 for the respective T-S and T-N relations as a cursory assessment of regional differences over the 300km coastal study region. Oxidised nitrogen was selected as the representative nutrient as in this region waters are nitrogen limited with respect to the idealised Redfield ratio for optimal phytoplankton productivity (Ajani *et al*, 2001). While the oxidised nitrogen ranges and the slope of the T-N relation maintains alongshore coherence, temperatures suggest an alongshore cooling bias of 1-2°C to the south. To investigate regional differences, CSIRO cruise data from the slope-water source (200-400m depth) between latitude bands 31° and 35°S were examined in Figure 4 (c,d) to indicate the coherence of slope-water to pre-determined temperature-nutrient criteria previously defined by Cresswell (1984); Humphrey (1960) from long term records collected off Sydney at Port Hacking. Water masses at the extreme latitude bands (31° and 35°S) are shown for temperature-salinity (T-S) and temperature-nutrient (T-N) plots in Figure 4 (c & d).

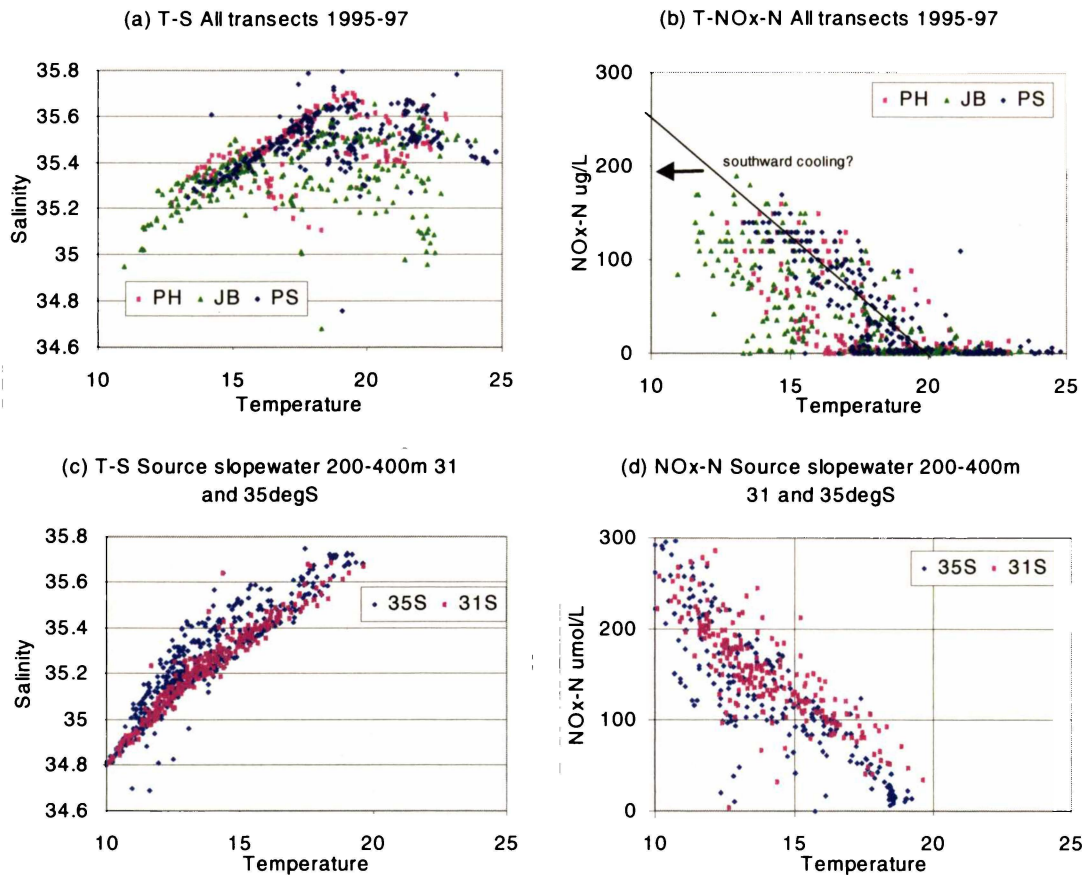


Figure 4: T-S (a) and T-NOx (b) relations for transect data collected at Port Stephens (PS), Port Hacking(PH) and Jervis Bay (JB); and (c&d), source slope-waters (200-400m) from 31°S and 35°S latitude bins.

Whilst alongshore temperature differences were apparent between the shelf transects, the alongshore slope-water is coherent between 31° and 35°S for both T-S and T-N conditions, suggesting shelf differences are localised and/or event based. T-S data (Figure 4 a & c), indicate slope-waters <15°C generally match the characteristics from the shelf transects. Whilst the slope of the T-N relation (and oxidised nitrogen ranges) from all shelf transects appear compatible with source slope-water criteria, temperature ranges from the most northerly transect off Port Stephens appears most consistent with the source slope-water (shown as a line in Figure 4b). This suggests that slope-water is most likely drawn onto the shelf in the vicinity of Port Stephens and cools as it advects southward along the shelf by the EAC.

The ORS record was again drawn upon to assess the typical oceanographic conditions associated with these intrusion events. From the 10-year record data was subset into periods of cool water (taken as $<15^{\circ}\text{C}$) and compared as distributions against the full record. To partition dominance of upwelling favourable winds and the EAC's alongshore flow, comparisons in Figure 5 were made for alongshore wind, alongshore surface current, temperature stratification and x-shelf bottom currents. Note that alongshore directions (component orientated to the alongshore axis $\sim 20^{\circ}$) obey oceanographic convention for both wind and currents as flowing towards. Distributions clearly associate cool intrusions with stratified EAC southward flows, and provide little indication of localised upwelling or favourable wind forcing, and support previous evidence that intrusions off Sydney are the result of remote upwelling occurring further to the north (eg. off Port Stephens).

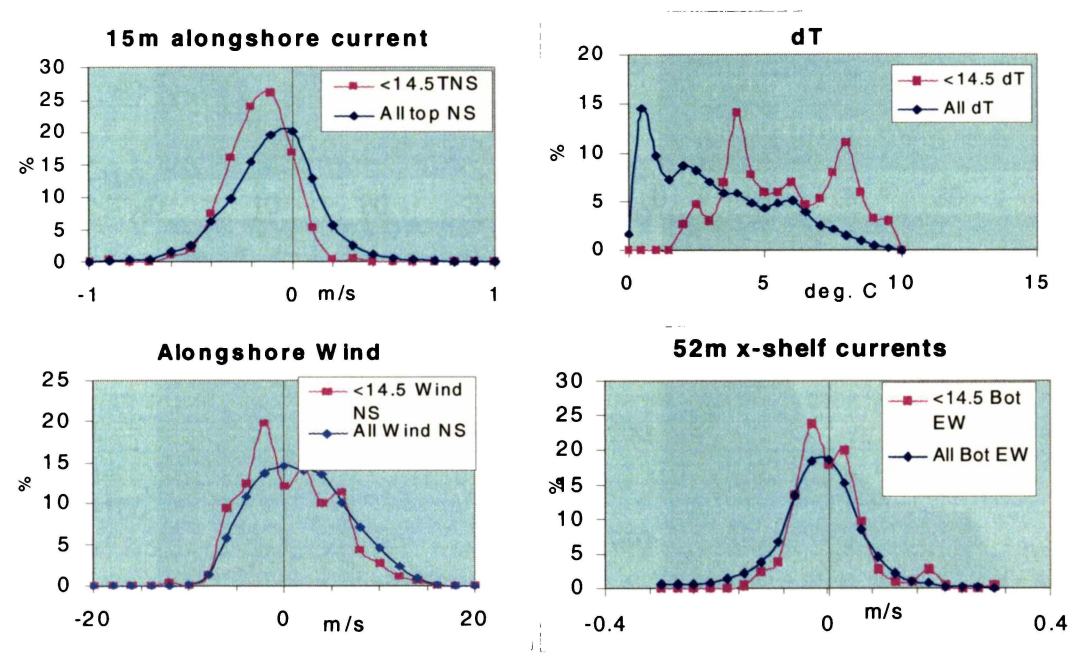


Figure 5: Distributions of alongshore current (15m) and wind components, temperature stratification (dT) and cross-shore currents (52m) from ORS records (1991-2000) for all data compared to conditions where 52m temperature is $<15^{\circ}\text{C}$.

Looking regionally at EAC on-shelf forcing, data from the ADCP transects and associated NOx-N sampling taken off Port Stephens and Jervis Bay during October 1995 - March 96 are sourced in Figure 6. These two regions provide examples of how local topography can cause instability to

EAC shelf flow and form localised mechanisms that can draw bottom waters inshore to the euphotic zone. The data identifies three distinct upwelling conditions that were experienced during this study. Two cases are provided for Port Stephens. Case "A" displays an EAC driven back-eddy seen here pumping nutrients up to the euphotic zone on the mid-shelf. The alongshore pressure gradient set-up in case "B" is driven by the direct stream drawing nutrients inshore in a bottom boundary layer. The case C for Jervis Bay is indicative of an alongshore EAC flow truncated by the local topography as the embayment heads protrude ~5 km off shore of the NSW coastal alignment. This effect drives a shoreward flux of nutrients into the bay at depth, as suggested by Blackburn and Cresswell (1993) as the mechanism that supplied the 1992/93 *Gephyrocapsa oceanica* bloom in Jervis Bay.

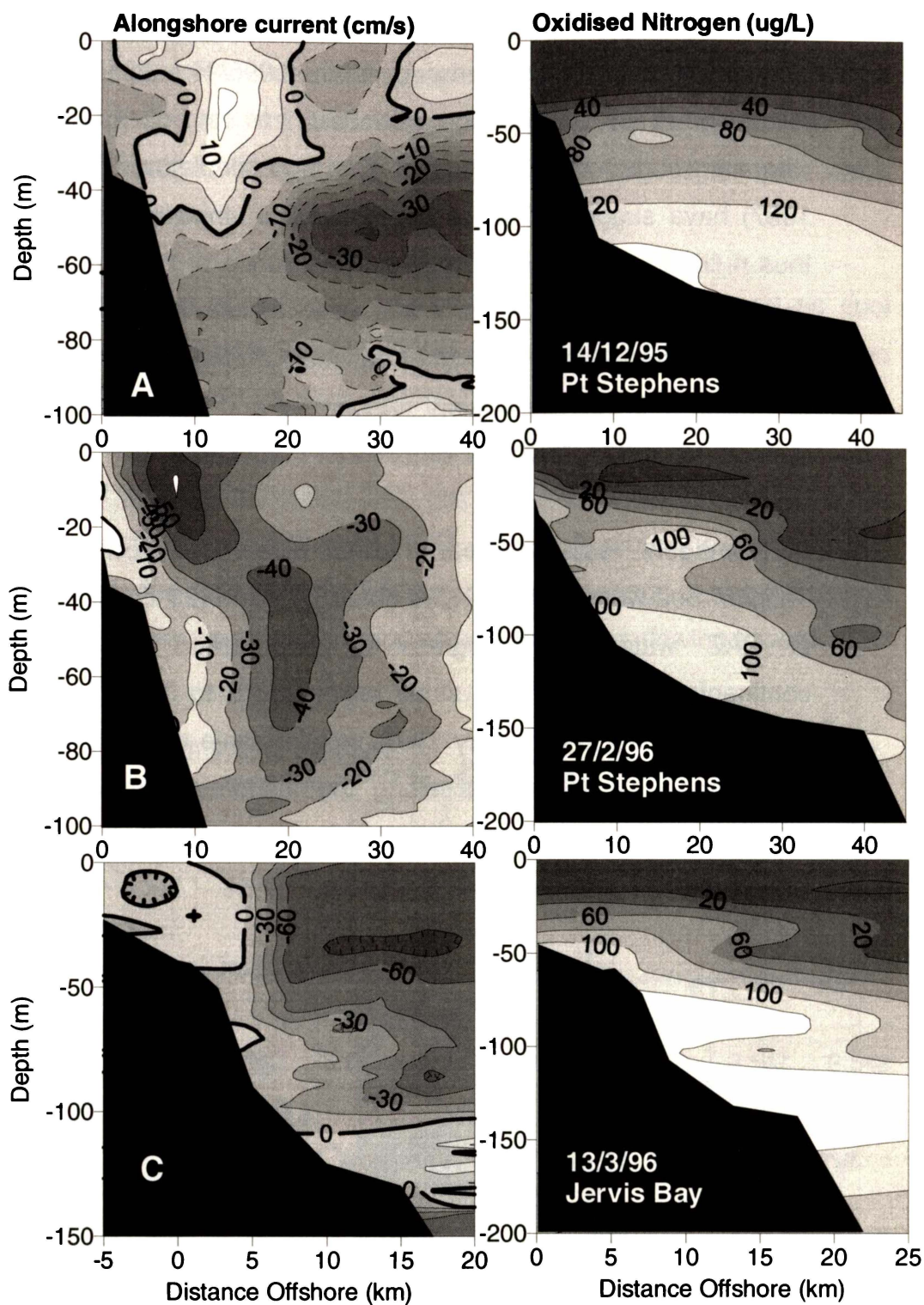


Figure 6: Alongshore currents (+ve northward in cm/s) and nutrients (ug/L) associated with (A) back-eddy formation at Port Stephens, (B) strong EAC pressure gradient at PS; and (C) EAC driven injection of nutrients into Jervis Bay.

Upwelling responsive studies: December 1996 to March 1997

The responsive sampling campaign of the 1996/97 summer detailed in the following section, focuses on Port Stephens and Jervis Bay transects, where previous modelling studies (Oke and Middleton, 2001; Gibbs et al., 1997) have suggested were predisposed to slope water intrusions, and thus nutrient enrichments. Routine surveillance of the regional dynamics and meteorological conditions was used to identify upwelling scenarios and trigger 'responsive' sampling transects during the period with the aim to explain and quantify nutrient enrichment and phytoplankton responses during and immediately after slope water intrusions.

SST imagery resolved clear thermal differences between Coral and Tasman Sea waters off the NSW coast. A warm (23°C) southward stream of EAC water that progressively encroached Australia's eastern continental shelf within the study region (33°S to 36°S) occurred during December 1996. By January 1997, smaller scale topographic instabilities had formed as backeddies along the inshore edge of this EAC jet, associated with changes in the orientation of the continental shelf (Figure 7).

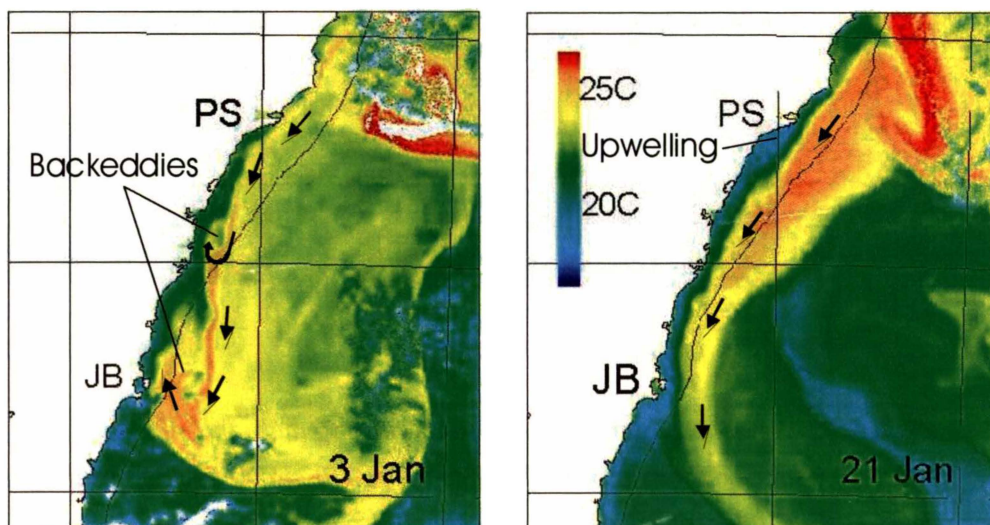


Figure 7: NOAA SST imagery showing the encroachment of the EAC and its interaction with coastal topography during January 1997.

With increased EAC forcing at the northern end (Port Stephens) later in January 1987, cool water inshore of the EAC front was indicative of upwellings in the lee of PS and JB promontories. By February 1997, the EAC shelf-fronts had dispersed, swamping the study region with warm (22°C) EAC water.

The presence of upwelling in the coastal region was sensed as cool intrusions in the bottom layer that were recorded ~150km apart at the two mooring sites off Port Stephens (PS03) and Sydney (ORS) in Figure 8. A series of upwelling episodes were concurrently detected at these sites associated with the intensified EAC activity on the shelf in late December 1996 through to mid February 1997. Figure 8 plots the temperature, current and wind data from the PS03 and ORS moorings during this period of upwelling, with currents and wind shown as vectors flowing toward.

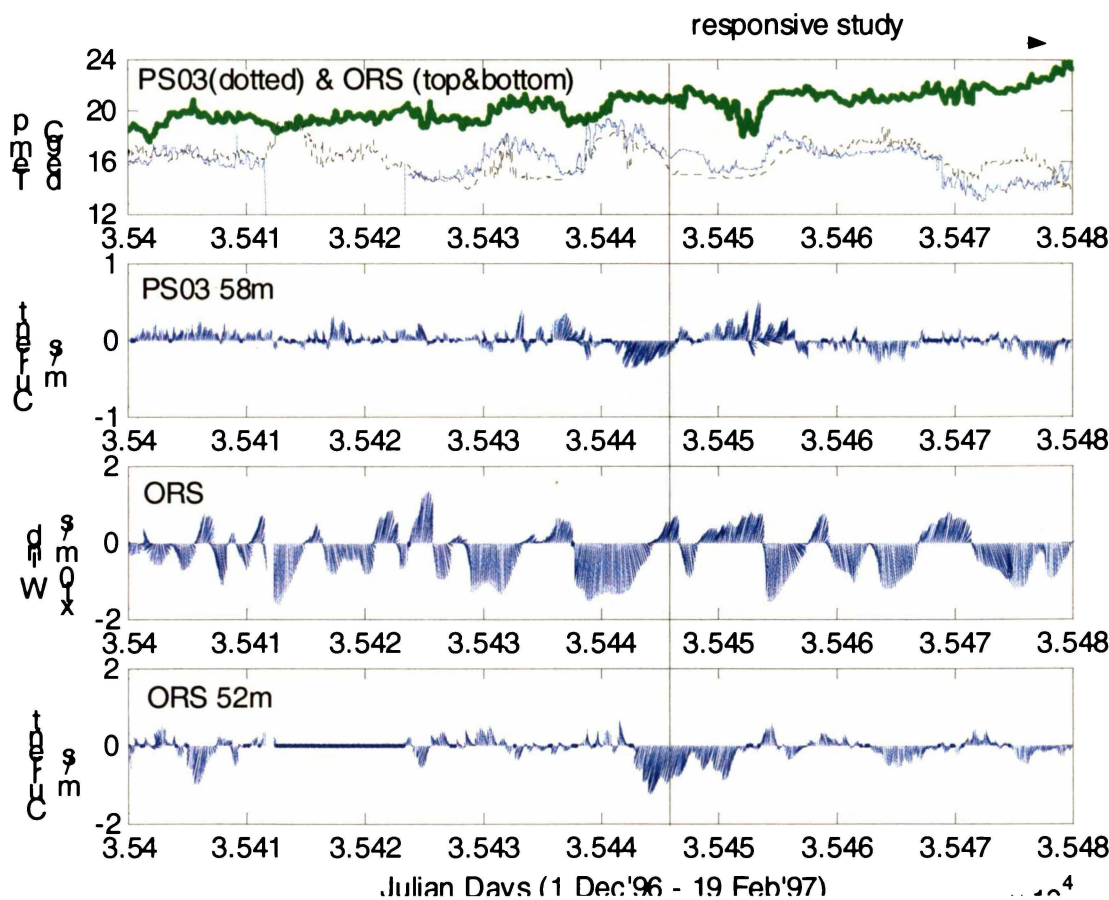


Figure 8: Time series records from the ORS and PS03 during the summer period December 1996-February 1997 (line indicates responsive study period), showing intrusions with respect to temperature records, bottom layer current vectors and wind vectors (flowing towards).

The data in Figure 8, indicate upwelling periods ranged between a 5 to 20 day duration and occurred at cycles of 10 to 20 days, with significantly longer durations occurring at PS03. PS03 intrusions in January 1997 occurred 2-3 days earlier than at the ORS, corresponding to typical EAC advection rates ($\sim 0.5 \text{ m.s}^{-1}$) between Port Stephens and Sydney. The intrusions in late December 1996 and early February 1997 were coherent and in phase with upwelling favourable north-easterly winds, and occurred over a typical 5-10 day weather-band.

The prolonged intrusions seen at PS03 (with respect to the ORS) in the January 1997 upwelling were incoherent with alongshore wind forcing, and punctuated by pulses of warm southward flowing water corresponding to shoreward migration/intensification of the EAC and downwelling favourable winds. Whilst there is alongshore coherence for the slope-water intrusions (neglecting the initial lags) in January 1997, bottom layer currents at PS03 and the ORS are opposed, supporting local topographic effects observed in the SST imagery (Figure 7) are controlling circulation patterns. With reference to the upwelling mechanisms shown in Figure 6, the coherence of northward flow at PS03 and intrusions of cool water relates to the formation of a clockwise back-eddy (Figure 6 "Case A"), whereas the prevailing southward flow at the ORS is more indicative of the EAC alongshore pressure gradient. Subsequent studies in this region during the following austral summer of 1997/98, repeatedly observed these mechanisms, and SeaWiFS satellite images of chlorophyll-a reflectance confirmed the importance of the backeddy cell off Port Stephens in enhancing the regional phytoplankton abundance (Lee et al, 2001). The EAC driven upwelling event in January 1997 became the focus for sampling transects at Port Stephens and Jervis Bay.

It should be noted that rainfall patterns were considered during the study period as a nutrient source from catchment run-off. Coastal catchments in this study region typically have well developed estuarine sections that only contribute significant nutrient loads (predominantly as silica) to coastal

waters after periods of heavy rainfall when the flood layer is able to overcome the salinity gradient (Lee et al, 1999). With respect to the periods of upwelling, the widespread rainfall that was recorded in late January and mid February 1997 (peaks of 60-80 mm.day⁻¹) did not register as flood levels in the catchments, and therefore indicated a negligible input to the nutrient budget in adjacent coastal waters.

Although responsive investigations were restricted to Port Stephens and Jervis Bay, visible blooms were also observed across other areas within the study region when periods of warm and stable weather conditions followed nutrient enrichment of inner shelf waters. These visible blooms were dominated by the neritic heterotrophic dinoflagellate, *Noctiluca scintillans* (between Port Stephens and Jervis Bay) or, to a lesser extent the tropical blue green algae *Trichodesmium* sp. (Sydney to Evans Head). Responsive investigations were completed during the periods from 18-31 January (Port Stephens) and 22 January to 13 March 1997 (Jervis Bay) along transects and at sampling stations respectively shown in Figures 1 and 2.

Port Stephens Investigations

The upwelling and subsequent diatom bloom event off Port Stephens during January 1997, is provided as cross-shelf profiles in Figures 2a and 9. Figure 2a depicts the temperature and associated nutrient concentrations at the peak of the upwelling on 18 January 1997, whilst chlorophyll concentrations and remaining nutrients are shown in Figure 9. A summary of physico-chemical data collected from four Port Stephens transects on 18, 24, 29 and 31 January is shown in Figure 10 for an inshore station 3 km from shore (60m), while phytoplankton results are summarised in Table 1. Understanding that these transects only provide fixed two dimensional snap shots of a three dimensional, and perhaps rapidly changing, dynamic, the PS03 current mooring (located at station 2 along the transect) is a good reference for continuity between the transects.

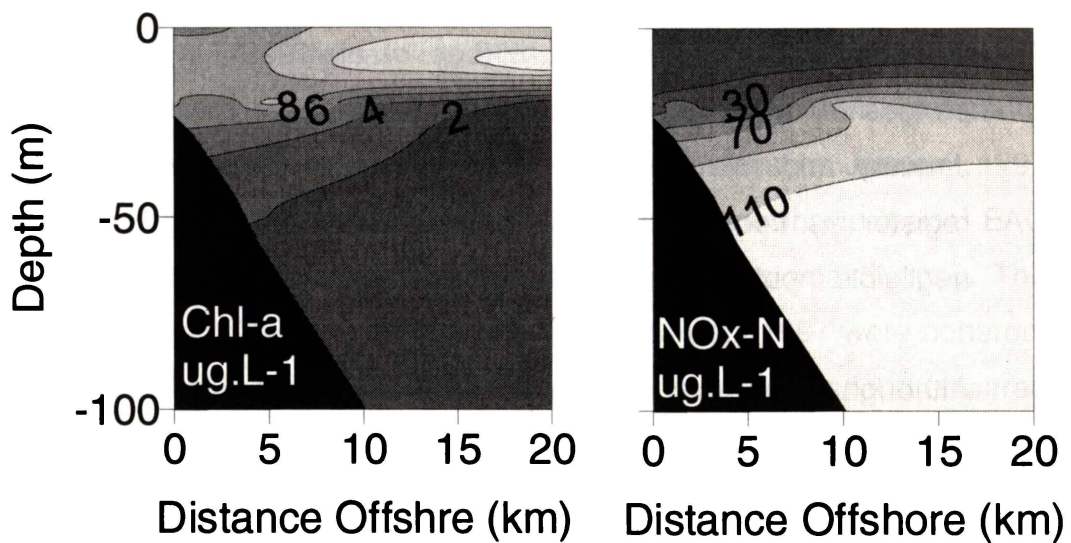


Figure 9: Oxidised Nitrogen and Chlorophyll-a transects during the peak diatom bloom at Port Stephens on 24 Jan'97.

PS03 data in (Figure 8) indicates an intrusion had occurred between 4-9 January, and a second intrusion had started on 15 January 1997. These were both associated with northward flows and separated by a strong southward pulse of warm water. SST thumbnail images during January in Figure 7 indicate the development of a back-eddy inshore of the EAC front and south of the main topographic protrusion of Point Stephens. Time series analysis (using wavelets) of the predominant alongshore current component at PS03 confirmed the peak energy during the entire 4-month deployment is associated with these back-eddy formations.

The transects captured the initial EAC driven intrusion typified by high nutrient levels in coastal waters. Silica, nitrate and phosphate maxima were in excess of 280 $\mu\text{g.L}^{-1}$, 130 $\mu\text{g.L}^{-1}$ and 22 $\mu\text{g.L}^{-1}$, respectively, while plankton by-products of chlorophyll-a and ammonia-nitrogen concentrations remained unstructured and near background levels. Within six days a rapid response from diatom populations had occurred, with *Thalassiosira* dominating populations in the vicinity of the EAC front (mid-shelf). In the surface layer concentrations of chlorophyll-a increased significantly (10-15 $\mu\text{g.L}^{-1}$) and corresponded with a reduction in light transmissivity (20%) and nutrients (~70% (silica <60 $\mu\text{g.L}^{-1}$; nitrate <20

$\mu\text{g.L}^{-1}$; phosphate $<8 \mu\text{g.L}^{-1}$). The following transect some 5 days later captured a *Noctiluca* bloom (alive and dead cells), and diatoms *Cerataulina*, *Leptocylindrus* and *Rhizosolenia* species embedded in the mucilage. Further offshore ($>5\text{km}$), no *Noctiluca* were found and the diatoms *Cerataulina*, *Leptocylindrus*, *Eucampia*, *Pseudonitzschia* and *Thalassiosira* dominated net haul samples. Downwelling subsequently isolated inshore waters from nutrient supplies and communities returned to ambient concentrations. In the last two transects, increased ammonia concentrations exhibiting a vertical gradient ($20 \mu\text{g.L}^{-1}$ near the surface to about $40 \mu\text{g.L}^{-1}$ at 60m depth), reflected the decay and subsequent sinking of phytoplankton material.

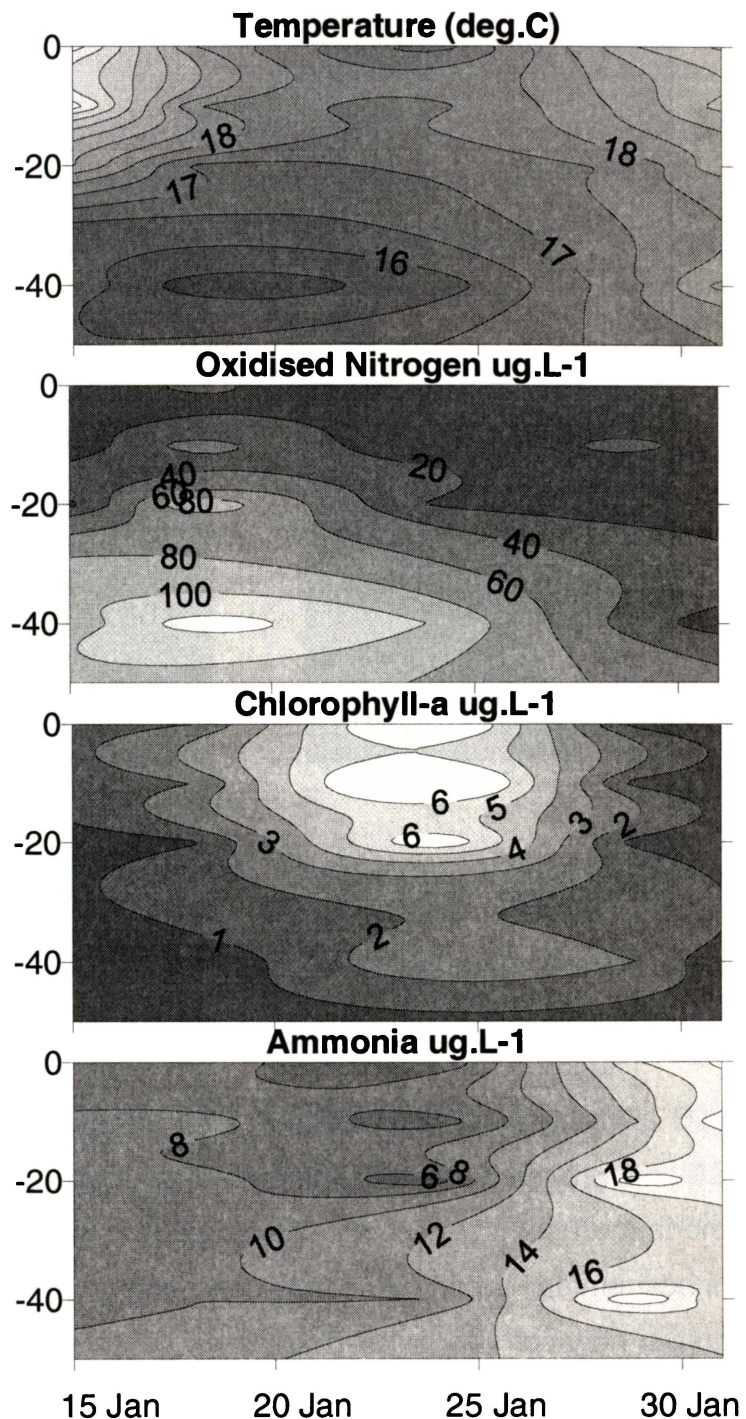


Figure 10: Time series of Temperature, oxidised nitrogen, chlorophyll-a and Ammonia at inshore station (3km offshore) during the bloom successions at Port Stephens.

Table 1 Summary of Phytoplankton Responses at Port Stephens

Date	Sites	Max. chlor-a (µg.L-1)	Max. total cells (per litre)#	Dominant Genera (net hauls)
18-Jan-97	1-9	2	1.31×10^6	Unidentified microflagellates and nanoplankton, <i>Chaetoceros</i> , <i>Rhizoselenia</i> (inshore only), <i>Thalassiosira</i> (offshore only) (<i>Noctiluca</i> observed)
24-Jan-97	1-6	16	7.59×10^6	<i>Asterionella</i> , <i>Chaetoceros</i> , <i>Lauderia</i> , <i>Thalassiosira</i> , <i>Pseudonitzschia</i> , <i>Rhizoselenia</i>
29-Jan-97*	1-9	3	9.66×10^5	<i>Noctiluca</i> , <i>Cerataulina</i> , <i>Leptocylindrus</i> , <i>Rhizoselenia</i> (inshore only), <i>Eucampia</i> , <i>Pseudonitzschia</i> , <i>Thalassiosira</i> (offshore only)
31-Jan-97	1-5	1	3.53×10^5	<i>Noctiluca</i> (inshore only), dinoflagellates and unidentified microflagellates

*visible *Noctiluca* bloom;

only samples with chlorophyll-a > 1 µg.L-1 were enumerated

Jervis Bay Investigations

The upwelling and subsequent diatom bloom event off Jervis Bay is provided as cross-shelf profiles in Figures 2 & 11 respectively. The sampling transect extended from 5km within the Bay to the mid-shelf 10 km offshore (depth 130m). Figure 2 depicts the temperature and associated nutrient concentrations at the peak of the upwelling on 22 January 1997, whilst peak chlorophyll concentrations (and remaining nutrients) associated with the initial diatom bloom on 29 January 1997 are shown in Figure 11.

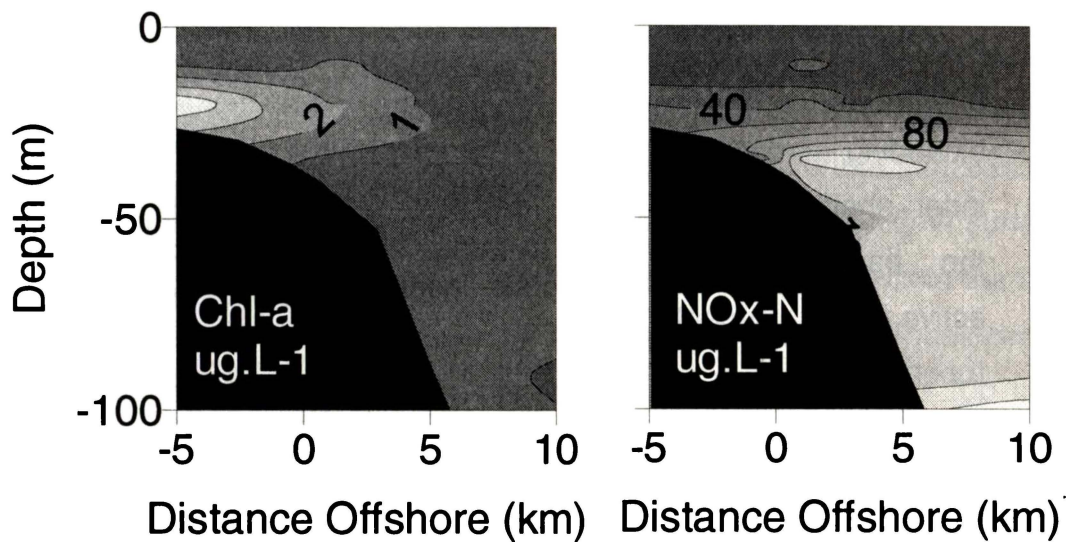


Figure 11: Chlorophyll-a and NOx-N transects during the peak diatom bloom at Jervis Bay on 29 January 1997.

A time series of physico-chemical data collected from seven Jervis Bay transects on 8, 22 and 29 January and 5, 19 and 28 February and 12 March 1997 is shown in Figure 12 for an inshore station 3 km from shore (60m), while corresponding phytoplankton observations are summarised in Table 2. Whilst no current mooring was deployed at this location during this exercise, ORS information (~150 km to the north) has subsequently proved to be an accurate guide to major EAC and weather driven circulation. From over twenty deployments of thermistor strings in coastal waters between Port Stephens and Jervis Bay during 1997 and 1998, the records between Sydney and Jervis Bay were in phase and significantly coherent between $1e^{-3}$ cph (42 days) to $6e^{-3}$ cph (166 hours) (Lee et al, in

prep). Reference to the ORS data in Figure 9 is therefore made to provide continuity to the transect snapshots.

The transects in late January 1997 initially captured anomalously cool bottom water extending across the inner shelf and into the bay indicating active, or recent (upstream), intrusions of slope water. This was associated with enhanced nutrient levels (240 $\mu\text{g.L}^{-1}$ of silica, 110 $\mu\text{g.L}^{-1}$ of nitrate, and 22 $\mu\text{g.L}^{-1}$ of phosphate.

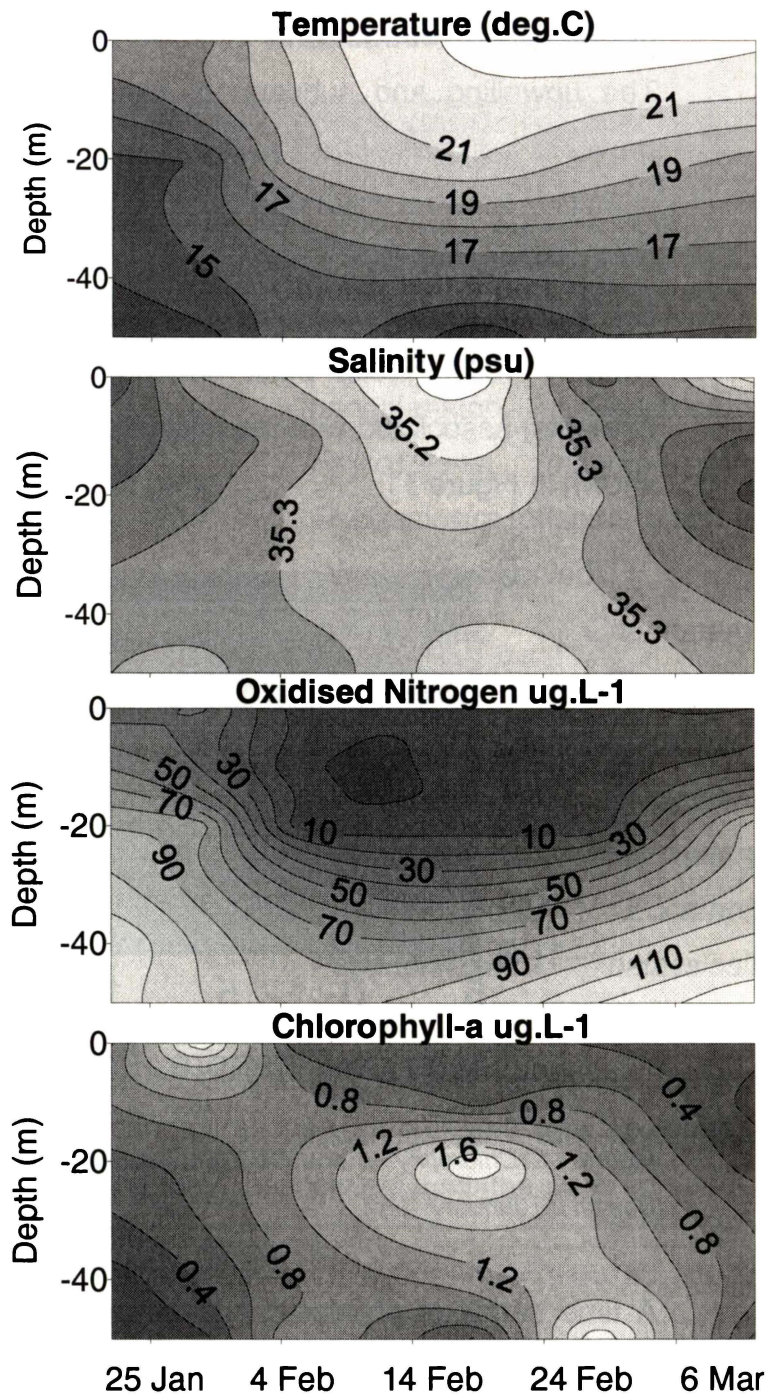


Figure 12: Time series of Temperature, salinity, oxidised nitrogen, and chlorophyll-a at inshore station (3km offshore) during the bloom successions at Jervis Bay.

While remnant populations of large dinoflagellates *Prorocentrum* and *Ceratium* (that had been observed actively reproducing in early January) were present in the bay, low chlorophyll-a and corresponding diatom numbers indicated this recent intrusion had not yet been sequestered. A week later, high chlorophyll-a concentrations (up to 5 $\mu\text{g.L}^{-1}$) were found in the surface waters within the bay, associated with the chainforming

diatoms, *Chaetoceros* and *Thalassiosira* species. A visible (surface) *Noctiluca scintillans* bloom was observed within Jervis Bay seven days later on 4 February 1997 and was observed for 3-4 days. Net hauls from within Jervis Bay were dominated by dead *Noctiluca* cells and unidentified nanoplankton with no evidence of the previous diatom flowering. Outside the Bay, live cells of *Noctiluca* were observed together with evidence of mucoid webs. These webs are secreted by *Noctiluca* to scavenge particles for ingestion (Uhlir 1990). By this stage the intrusion had retracted seaward leaving embayment waters exhausted of nutrients (nitrate $<10 \mu\text{g.L}^{-1}$, phosphate $<4 \mu\text{g.L}^{-1}$ and silica $<60 \mu\text{g.L}^{-1}$), whilst high ammonia levels within the bay and at the thermocline immediately outside the heads, were indicative of plankton decay. Within the following two weeks, this exhausted system was replenished by further intrusions to inner shelf waters, and heavy rainfalls causing reduced salinity in surface layers within the bay. *Noctiluca* mucoid webs were present within the bay and offshore and associated with chainforming diatoms *Chaetoceros*, *Pseudonitzschia* and *Skeletonema* and increased chlorophyll-a (up to $5 \mu\text{g.L}^{-1}$). By late February 1997, *Noctiluca* was still observed at all stations along with the flowering of a large diatom *Rhizosolenia*, but dead *Noctiluca* cells were increasingly observed inside the bay. By mid March 1997, all plankton populations returned to ambient background levels, with only senescent *Noctiluca* cells as a remnant of the bloom successions that had occurred over the two-month period.

Table 2 Summary of Phytoplankton Responses at Jervis Bay

Date	Sites	Max. chlor-a ($\mu\text{g.L}^{-1}$)	Max. total cells (per litre)#	Dominant Genera (net hauls)
8-Jan-97	1-2	Not sampled	Not sampled	<i>Prorocentrum</i> , <i>Ceratium</i> , coccolithophorids and unidentified nanoplankton (<i>Noctiluca</i> observed)
22-Jan 97	1-5	1	8.1×10^5	<i>Prorocentrum</i> (inshore only), <i>Chaetoceros</i> , <i>Skeletonema</i> , <i>Pseudonitzschia</i>
29-Jan-97	1-6	5	2.4×10^6	<i>Chaetoceros</i> , <i>Thalassiosira</i> , <i>Pseudonitzschia</i> , <i>Cerataulina</i> , <i>Leptocylindrus</i> (<i>Noctiluca</i> observed)
5-Feb-97*	1-6	2	5.55×10^5	<i>Noctiluca</i> (inshore only), unidentified nanoplankton, <i>Ceratium</i> , <i>Prorocentrum</i> , <i>Chaetoceros</i> , <i>Rhizosolenia</i> , <i>Thalassiosira</i>
19-Feb-97	1-6	5	2.16×10^6	<i>Noctiluca</i> , unidentified nanoplankton, coccolithophorids, <i>Chaetoceros</i> , <i>Pseudonitzschia</i> , <i>Skeletonema</i>
28-Feb-97	1-6	3	3.24×10^5	<i>Noctiluca</i> (inshore only), <i>Rhizosolenia</i>
12-Mar-97	1-6	2	2.38×10^5	<i>Noctiluca</i> , dinoflagellates and unidentified microflagellates

*visible *Noctiluca* bloom

only those samples with chlorophyll-a > 1 $\mu\text{g.L}^{-1}$ were enumerated

Discussion

From these studies undertaken, mechanisms and scales of upwellings were assessed during January and February 1997, and were relatable to subsequent phytoplankton patterns.

Time series data identified coherent upwellings associated with wind forcing during December 1996 and February 1997 over the ~150 km between moorings off Port Stephens (PS03) and off Sydney (ORS). However the protracted event in January 1997 was related to shelf encroachments of the western boundary flow, the East Australian Current. EAC circulation effects caused by local coastal topography were apparent from SST imagery. Alongshore lags attributable to typical alongshore flows of the EAC were apparent in time series records, and reflected in phytoplankton bloom peaks. The localised upwelling mechanisms that drove the January 1997 intrusions at Port Stephens and Jervis Bay were similar to the scenarios depicted in Figure 6 during the 1995/96 summer as primarily driven by EAC interactions with inshore topography.

From long term records off Sydney, inshore waters are typically low in nutrients and, in particular, nitrate limited (surface layer ~20 $\mu\text{g.L}^{-1}$; bottom layer ~40 $\mu\text{g.L}^{-1}$) with respect to optimal conditions for phytoplankton growth (Lee et al, 2001). Similar concentrations (and ranges) are also found from transects taken during ambient conditions off Port Stephens and Jervis Bay, although temperature ranges associated with the nutrient distributions show a southward cooling bias (of 1-2°C) as the Temperature-NO_x-N plots in Figure 5 suggest. The slope-water intrusions in January 1997 brought an initial injection of NO_x-N (60-120 $\mu\text{g.L}^{-1}$) and SiO₂ (80-200 $\mu\text{g.L}^{-1}$) to inshore waters at both locations. This was rapidly consumed by diatoms to bring levels well below ambient at <10 $\mu\text{g.L}^{-1}$ and <60 $\mu\text{g.L}^{-1}$ respectively and experienced along both the Port Stephens and Jervis Bay transects. Looking at a cross-section of inshore waters (surface layer depths shown for 0-10km offshore) in Figures 10 and 12, this nutrient uptake by phytoplankton occurred in a 20-10m layer off Port Stephens and a 30-20m layer off Jervis Bay. Although overall loads were

~double off Jervis Bay, the phytoplankton response (as indicated by cell counts and chlorophyll concentrations) in the warmer waters off Port Stephens doubled the response off Jervis Bay.

Whilst the intrusions were the clear nutrient source during this study, the evidence of low salinity lens in Jervis Bay associated with rains in late January required addressing. In general the diatom blooms depleted all nutrients in upper 30m, but FRP distributions show an apparent rainfall correlation with a surface enrichment of 4-8 $\mu\text{g.L}^{-1}$ in the upper 10m that moves offshore by 19 February 1997. It is suggested that this event provided more optimal conditions for phytoplankton by lowering salinity rather than providing this small increase in FRP. This is particularly so for *Noctiluca* which ranges over salinities of 14-35 psu but has optimal growth at 20-25 psu (Murray and Suthers, 1999). Lenses of <35.1 psu seen in the top 5-10m of the bay were present on transects after the main falls, which could explain the staggered chlorophyll responses in Jervis Bay in late January and mid- February.

A number of similarities in the phytoplankton responses were seen during the events at Port Stephens and Jervis Bay. Nutrient rich intrusions were rapidly sequestered by diatom blooms, which provided critical prey mass for subsequent rapid growth of *Noctiluca* until the diatom blooms collapsed (due to exhausted nutrients and predation by *Noctiluca* as seen in bloom pole samples). This food limitation prompted a *Noctiluca* collapse expressed as visible surface bloom (starving cells with large empty food vacuoles float to form bloom) which occurred some 5-7 days after the diatom peak. The blooms coincided with transient high ammonia concentrations due to microbial decay of both diatoms and *Noctiluca*, afterwhich the phytoplankton community returned to relatively low numbers (dominated by dinoflagellates and unidentified microflagellates), that were typical for this time of year. Both bloom events occurred inshore of the main EAC front that bounded the inshore waters during January. Offshore species such as *Thalasiosira* were associated with the warmer

waters of the EAC that were brought inshore with the EAC shelf encroachments.

The prolonged intrusion at Jervis Bay during January was "refuelled" by a second intrusion in mid February, which amalgamated populations of various ages and maintained elevated concentrations through to March. The Jervis embayment compounded this effect by enabling retention of phytoplankton populations for up to a month and exposed them to low salinity waters associated with heavy rains in late January. The open ocean condition at Port Stephens clearly defined the phytoplankton succession from diatoms to *Noctiluca*, with none of the latter present in samples taken earlier in the upwelling. Back-eddy retention times (observed as 5-15 days from the PS03 mooring) maintained the standing stock, but subsequent swamping by the EAC and offshore retraction ensured the recovery to ambient conditions was similarly swift.

Gibbs et al (1997) modelled the scenario that led to the large *Gephyrocapsa oceanica* bloom in Jervis Bay during the 1992/93 summer, and produced baroclinic instabilities on the inshore edge of stable warm core eddies that injected cold nutrient rich waters into the embayment. These instabilities manifested as cold core eddies that brought unseasonably cool water (14-18°C) throughout the embayment. The resulting bloom seeded from offshore waters, was sampled at ubiquitous densities of 2.0×10^6 cells.L⁻¹, with peaks at 1.8×10^7 cells.L⁻¹ (Blackburn and Cresswell, 1993). Samples taken within Jervis Bay by the NSW EPA in January 1993 (NSW EPA unpublished data) indicated initial concentrations of NO_x-N (60 µg.L⁻¹) within the bay on 6 January 1993 had become exhausted by 12 January 1993 to <10 µg.L⁻¹. The more prolonged scenario during January - March 1997 showed initial similarity with forcing conditions and high nutrients (NO_x-N up to 100 µg.L⁻¹ in the bay), but the encroaching EAC eddy soon swamped bay waters raising surface temperatures up to 22°C. Also of note during this period were significant short-duration rainfalls in late January (90mm) and mid February (150mm) producing an observable fresh surface lens, whereas in

January 1993 falls were below average at 60mm. The initial diatom bloom and succeeding *Noctiluca* bloom had similar densities of $\sim 2 \times 10^6$ cells.L⁻¹, matching the averages seen in 1993 . Whilst it appears both scenarios experienced similar concentrations of nutrient enrichment, the apparent physical differences (EAC encroachments and rainfall) may have contributed to cause more favourable conditions for either *Gephyrocapsa oceania* or *Thalassiosira/Noctiluca*. However, considering the observed bloom lags for *Noctiluca* between Port Stephens and Jervis Bay in 1997, and the warm water preference of all three species, the preceding conditions within the EAC eddy that maintained the phytoplankton stock may well outweigh prevailing regional shelf conditions in the expression of the coastal bloom.

The recent focus on *Noctiluca* (Dela-Cruz et al, 2002) raises concerns of its association with anthropogenically impacted coastal regions, such as in SE Asia (Ya and Xin, 1993; Adnan, 1989), and its effect on the ecosystem. Whilst considered non-toxic, *Noctiluca* may have an enormous impact on plankton, as recent studies by Murray and Suthers (1999) suggest it doesn't grow in cultures unless phytoplankton concentrations are $> 2 \times 10^4$ cells.L⁻¹, and with competitive doubling times 6-48 hrs is often dominating zooplankton populations. It also shows a preference for warmer waters and food (5-25 μ m) with *Thalassiosira* considered optimal diatomic fodder in laboratory studies by Buskey (1995). Competitive advantages of the large colony-forming species, *Thalassiosira partheneia* over other phytoplankton, though not tested in Australian waters, has been observed elsewhere by Smayda (1997).

Long-term climatic studies in the study region have indicated oscillations of temperature (increased) and nutrients (reduced) are related to the inter-annual variation of El Niño, significantly varying the seasonal signal of these parameters by $\sim 30\%$ (Lee, et al, 2001). In their studies, the 1997/98 El Niño was shown to cause similar temperature and nutrient anomalies. Species dominance in diatom blooms were also shown to follow this variance, with *Thalassiosira partheneia* favoured by El Niño conditions,

while *Pseudonitzschia* dominated populations in cooler years. Combined with its preference for warmer water and association with *Thalassiosira partheneia*, it is a reasonable assumption that while these bloom successions appear linked to seasonal EAC shelf encroachments, an inter-annual climatic signal may also affect the dominance of *Noctiluca* populations.

To consider whether the sampling intervals at Port Stephens and Jervis Bay were adequate to capture dynamics and successions, temporal scales from the PS03 and ORS mooring records are referenced. At Port Stephens intrusion events lasted for 5-15 days and cycled between 5 and 20 days during this study period. For Jervis Bay the large scale intrusions (as indicated from ORS data) suggest similar scales extended through February and March. However localised topographic control of the alongshore EAC flow, embayment isolation from offshore dynamics and an influence of rainfall in the surface layer were factors that may have challenged the sampling frequency. Physically it appears the sampling was adequate to capture the significant events seen in the time series data. Whilst the succession from diatoms to *Noctiluca* bloom was well documented by the sampling, the initially rapid response by diatoms required a higher sampling frequency.

Conclusion

Intrusions of nutrient rich water from the shelf slope observed during 1995-98 on Australia's eastern shelf, were frequently driven by shelf interaction with the region's western boundary gyre, the East Australian Current. Whilst weatherband intrusions (5-10 days) correlated to favourable windforcing, the prolonged events (such as the focus of this study in January 1997) were associated with stratified southward seasonal flows of the EAC. Historical records (back to 1942) confirm the importance of the seasonal signal, and long-term time series data (1991-2000) supports the dominance of stratified EAC flows associated with these intrusions.

Initial indications are that, for at least this sampled event, upwellings can operate from regional to meso-scale (several hundreds of kilometres) and exhibit similar phytoplankton responses/ successions. However the local environment can modify this regional forcing by significant anomalies in coastal topography, and subsequently influence the behaviour of the phytoplankton populations. Both of the environments studied showed similarities as phytoplankton "incubators", as back-eddying formed in the lee of Point Stephens, and by physical restraint within Jervis Bay. This retention ability can have significant implications for the regional ecosystem as experienced in Jervis Bay with the 1992-93 *Gephyrocapsa oceanica* bloom, when established penguin colonies were vacated for several weeks until ambient conditions returned. These two retention mechanisms allowed the diatom-dinoflagellate bloom succession to be resolved by repetitive sampling transects. Whilst similar lags in diatom peaks and subsequent *Noctiluca* growth (after critical prey mass of diatoms was achieved) were observed at both locations to follow the initial nutrient intrusion, the local environmental flushing capacity determined the system's ability to return to ambient conditions.

The potential for offshore seeding of coastal phytoplankton populations from warm waters of the EAC coincides with seasonal patterns of coastal upwelling in this region, causing these tropical species to be the most common bloom species in these temperate coastal waters. Inter-annual enhancements of temperature during El Niño, favouring *Thalassiosira partheneia* have been indicated in supporting studies as an important determinant to the dominance of the *Noctiluca* blooms in this region. Ongoing phytoplankton monitoring encompassing the inter-annual signal, is needed to ensure this influence can be resolved from anthropogenic influences that are often cited as the main cause of *Noctiluca* blooms.

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5-3 CHAPTER CONCLUSIONS

The information within this chapter paper defines the oceanic nutrient intrusion patterns affecting coastal waters at several locations in the Australian study area and compares local conditions, in an attempt to address the third thesis objective. As the prevailing geostrophic flow impinged both shelf regions with similar water masses, the onshelf processes localised the respective nutrient compositions, and subsequently formulated unique corresponding algal responses. Companion plankton studies indicated that effects of these localised coastal enrichments were observed in coastal regions downstream of the measured scenario. The response patterns of algae identified in these scenarios, and their links to the physical processes, are developed further in the following chapter.

Chapter 6: Phytoplankton Responses

6-1 CONTEXT OF PAPERS WITHIN THE THESIS

As primary producers, phytoplankton require carbon dioxide, water, sunlight and nutrients to convert inorganic carbon into the organic matter of living cells. Photosynthesis delivers energy to the base of the food web via algae which are grazed by animals (zooplankton, etc.) which in turn are food for carnivorous animals (fish, etc.). As carbon dioxide and water are readily available to plankton, the abundance of light and nutrients often limits photosynthetic activity and thus algal growth. Environmental conditions, such as temperature, must be suitable for metabolic processes to operate, and even under optimum growth conditions the abundance of algae may be limited by the presence of grazing animals.

It is important to remember that there are many thousands of species of marine phytoplankton, each with its own set of optimum growing conditions, survival strategies and life cycles. For instance, although phytoplankton compete for all forms of nitrogen, some species thrive on certain forms (e.g. blue green algae can fix nitrogen from the atmosphere) and some species do better with constant low levels of nitrogen, while others prefer large bursts delivered by floods or ocean upwellings. Therefore, it is important to understand how, and in what form, various nutrient sources deliver their load to coastal systems. The first paper details sampling undertaken during and after a major coastal upwelling, tracking the physical and chemical patterns, and the associated biological responses. This paper was published in the *Journal of Coastal Research* in 2001, as the following reference.

Lee, R.S., Ajani, P.A, Wallace, S.. Pritchard, T.R., and Black, K.P., (2001). Anomalous upwelling along Australia's east coast, Journal Coastal Research, 34, p. 87-95.

The second paper provides an overview of phytoplankton responses on a seasonal scale, and was also published in the Journal of Coastal Research in 2001, as the following reference.

Ajani, P., Lee, R., Pritchard, T. and Krogh, M., (2001). Phytoplankton dynamics at a long-term coastal station off Sydney, Australia. Journal of Coastal Research, 34, p.60-73.

6-2 ANOMALOUS UPWELLING ALONG AUSTRALIA'S EAST COAST

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Running Head: Unusual algal bloom conditions captured off New South
Wales, Australia.

Abstract

Warm nutrient-poor water, associated with the 1997/98 El Niño, dominated conditions along Australia's east coast for the majority of 1997. Towards the end of the El Niño event, anomalously cool nutrient-rich water prevailed in coastal waters in response to a strong upwelling associated with enhanced dynamics from the East Australian Current and upwelling favourable winds. The upwelling was consistent with anomalously cool conditions observed during the demise of previous El Niño periods at the study location. Phytoplankton responses included blooms of the small centric diatom *Thalassiosira spp.* and the large heterotrophic dinoflagellate *Noctiluca scintillans*. Repetitive physico-chemical and biological sampling along cross-shelf transect lines combined with a 300km alongshore array of thermistor moorings, and ground-truthed SeaWiFS observations, captured this event. Enhanced East Australian Current activity to the north, and upwelling favourable winds across the study region, promoted cool nutrient-rich slope-waters to be uplifted onto the continental shelf. Thermistor records suggest this event swamped the entire study region in early January 1998 and remained until early February 1998. Cross-spectral phase analysis of the records confirms these spatial and temporal observations. Nutrient levels peaked at the 99%ile value of records from 57 years monitoring at the study location. Slope-waters uplifted to the euphotic zone, enhanced populations of both primary and secondary phytoplankton bloom species, which extended to mid February 1998. SeaWiFS imagery indicates the formation of a cyclonic back-eddy on the inshore edge of the East Australian Current, and in the lee of a major topographic protrusion. This back-eddy isolates slope-waters and incubates phytoplankton, leaking alongshore with the general southward streamflow. Assessments of the reproductive status and feeding activity of *Noctiluca* indicate a maturing population with increasing southerly extent, thereby supporting satellite observations.

Index words: Upwelling, El Niño, East Australian Current, New South Wales, *Noctiluca scintillans*

Introduction

On western oceanic boundaries the mean wind field is not conducive to the persistent upwelling, as seen at eastern boundaries off Peru, Oregon and NW Africa. However, transient upwelling favourable winds can lead to episodic coastal upwellings on a western boundary when durations of the favourable weather patterns persist for a day or more. This has been observed on the south-eastern US continental shelf by McClean-Padman and Padman (1991), who noted that the shelf off eastern Australia is similarly affected by upwelling favourable winds (from the NE sector) when high pressure systems are situated offshore. These events usually occur during summer months and persist for several days generating short-term coastal upwellings.

Cool water on the east Australian shelf off Sydney, was observed by Rochford (1959) during autumn and early summer irrespective of wind forcing, and was considered to originate further offshore from depths of >200m. Upwelled water 300km further to the north off Laurieton, in NSW was shown by Grant (1971) to be advected by a southward flowing current to the Sydney region. Pearce and Boland (1982) showed that this persistent alongshore flow at the shelf break caused an onshore Ekman flux of the bottom boundary layer. In accordance with geostrophy the western boundary current off the eastern seaboard of Australia, The East Australian Current (EAC), sets up an alongshore pressure gradient that tilts the sea-surface down towards the coast. This tilting causes a shallowing of cooler isotherms, which depending on the EAC's position with respect to the shelf-break, can provide nutrient rich waters to the shelf. This system streams poleward along the east coast, before diverging around 32°S to form the easterly propagating Tasman Front, and the EAC eddy field (Tranter et al, 1986). The anti-cyclonic EAC eddies advect Coral Sea water southward into the Tasman Sea forming dynamic thermal fronts of several hundred kilometres in length.

The turbulent eddy field often impinges on the shelf forming meanders and cyclonic back-eddies (order ~10s of km) that interact with topography and uplift cooler water to the euphotic zone. Cresswell (1994) observed bottom water temperature of $<13^{\circ}\text{C}$ off Sydney in association with a southward moving cold core eddy advecting along an EAC front further offshore. On-shelf EAC induced southward flows have been observed by Pearce and Boland (1982) to enhance bottom stresses on the mid-shelf, with currents in the bottom boundary layer flowing $30\text{--}40^{\circ}$ towards the shore.

To the north of this eddy field ($\sim 32^{\circ}\text{S}$), upwellings are often seen in the lee of topographic protrusions or where a narrowing of the shelf causes an acceleration of flow thereby enhancing onshore flow in the bottom boundary layer (Oke and Middleton, 1999). Nutrient enriched water on the shelf can be transported alongshore by the EAC to the eddy field where the various mechanisms described can uplift these waters to the euphotic zone. The increased nutrients are utilised by ambient phytoplankton populations, which can reach bloom proportions in coastal waters when combined with favourable environmental conditions.

Upwellings off the eastern Australian coast typically occur between spring-autumn seasons when the shelf waters are stratified and the flow of the EAC is strongest (Wyrki, 1960, 1962). Hallegraeff and Jeffrey (1993) suggest this seasonality to the EAC is responsible for the algal bloom patterns along the south-eastern Australian coast in New South Wales (NSW).

The seasonal dependence of phytoplankton bloom patterns in this region is shown by Hallegraeff and Reid (1986), and Harris et al (1987), to be a combination of the seasonal cycle and episodic events, resulting in spring and summer bloom seasons. Observations from the long term data records collected at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) station off Port Hacking (Sydney) NSW, indicate peak bottom water nutrients exist in February, whilst peak surface water nutrients

occur in Aug-Sept, thereby accounting for the two main algal bloom seasons (Lee *et al*, 2001). Studies on a 58-year long-term record by Pritchard *et al* (1998) suggest the predominant intrusions of nutrient rich slope-water occur during the austral spring (August-November). This is the result of the winter overturning of shelf waters which is depicted by a bottom-water temperature minimum and surface water nutrient maximum (Lee *et al*, 2000), and produces a consistent algal bloom that is predictable to within 3-4 weeks (Hallegraeff and Jeffery, 1993). The more episodic nutrient enrichment events in summer (Jan-April) appear related to short-lived EAC shelf disturbances (enhanced surface temperature/reduced bottom temperatures) or weatherband durations of upwelling favourable winds (north-easterlies reducing both surface and bottom temperatures).

Hallegraeff and Jeffery (1993) studied EAC on-shelf influences in relation to annually recurrent bloom activity on the NSW coast. They found the chlorophyll enrichments to be topographically related, suggesting that local mixing processes had an effect in drawing upwelled nutrients to the surface. They also note that blooms in this region can extend alongshore up to 700km in response to current induced upwellings. Modelling studies by Oke and Middleton (1999) proposed that localised uplifting of slope-water onto the shelf occurs in regions of shelf narrowing, where an active bottom boundary layer is driven by increased bottom stress. The slope-water is then advected alongshore on the shelf until the flow-stream encounters topographic disturbances that cause the flow to diverge and the slope-water to upwell. This phenomenon was suggested by Oke and Middleton (1999) as a mechanism that fed nutrient rich water into a back-eddy they simulated in the lee of the major topographic change at Port Stephens (~150km to the north of Sydney).

In late 1992 widespread plankton blooms occurred along the NSW coastline in response to prolonged periods of cool slope-water intrusions that were measured on the inner shelf off Sydney. The anomalous *Coccolithophorid*

(*Gephyrocapsa oceanica*) bloom in Jervis Bay between Dec'92 and Jan'93 responded to this prevailing nutrient source. Blackburn and Cresswell (1993) discounted localised effects of rainfall and anthropogenically derived nutrients and attributed the bloom to prevailing intrusions of cool nutrient rich slope-water.

Widespread blooms were again reported in the summer of 1998 on the NSW coast coinciding with observations of cool surface water present inshore (Ajani *et al*, 2000). The following paper details a strong intrusion event along the NSW coast during January 1998, and the succession of bloom activity that subsequently prevailed.

Data and Methods

Sampling Location and Frequency

Along a 300km stretch of the NSW coast, between Port Stephens and Jervis Bay, temperature and current (off Sydney only) information was collected from five instrumented moorings for the period December 1997-March 1998 to capture the unusually strong intrusion of cool bottom water that occurred in January 1998. Locations of these moorings are presented in Figure 1. Satellite imagery was also obtained for the duration of this event to indicate its extent along the coast. Phytoplankton assemblages and the associated physico-chemical environment were investigated offshore from Port Hacking, New South Wales, from weekly sampling in coastal waters and cross-shelf transects during the event period in January 1998.(see Figure 1).

Instrumental Data

Twenty thermistor moorings were deployed between Port Stephens and Jervis Bay during the period of July 1997-August 1998, to characterise the frequency and duration of slope water intrusions to the inner shelf. All instrumentation was located along the inner continental shelf, in water depths of 50-100m. Each thermistor mooring consisted of three StowAway® temperature loggers (range -5 °C to 37 °C; accuracy 0.1 °C), positioned at 2m, 10m and 20m above the bottom. The thermistors sampled hourly. A thorough analysis of these moorings over their full deployment period (LEE et al., in prep), indicated strong regional coherence. For the purpose of this paper representative regional moorings in 50-60m were selected for Port Stephens (PS03), Port Hacking (PH01) and Jervis Bay (JB05) to investigate coherence of the event in January 1998 (see Figure 1).

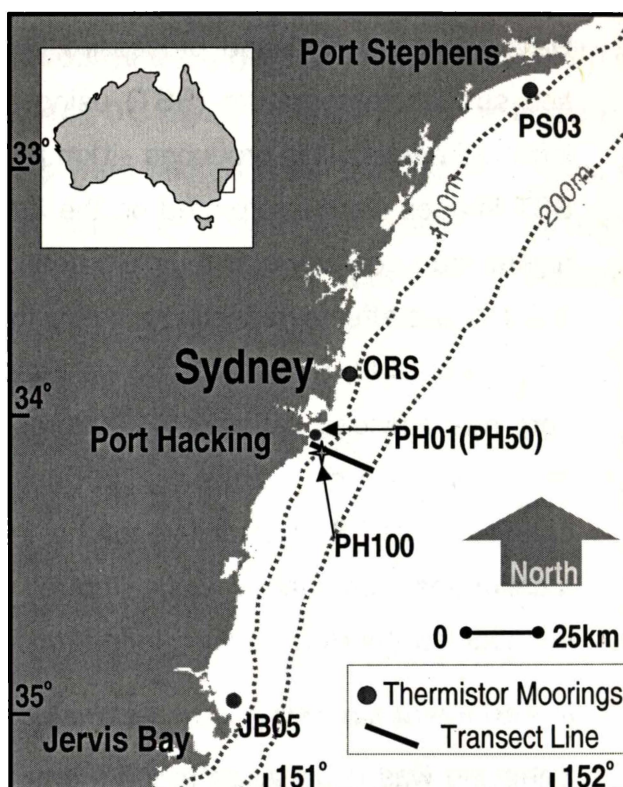


Figure 1. Locality diagram for alongshore instrument moorings and in situ sampling off Port Hacking during January 1998.

Continuous hourly temperature, current and wind records have been obtained from an instrumented buoy (the Ocean Reference Station, ORS) operated by Sydney Water Corporation. After initial trials in 1989, the ORS has been operating relatively continuously (apart from maintenance) ~4kms offshore of Bondi, Sydney in 65m of water since November 1990. The buoy was configured with two S4P current meters located at 17m and 52m depth,

16 thermistors on a chain spanning the upper 52m of the profile, and two anemometers measuring near-surface wind. Both the currents and winds have been orientated (by an averaged 13.5 alignment of the coast) into alongshore and cross-shelf components. Directions for both are given as flowing towards.

Surveillance of oceanic circulation patterns was based on images from the National Oceanographic and Atmospheric Administration (NOAA) series of Advanced Very High Resolution Radiometer (AVHRR) satellites which sense the visible, near infra-red and three thermal infra-red wavelength bands. Data were collected and processed by the CSIRO Marine Laboratories for sea surface temperature (SST) using a combination of two of the thermal infra-red bands. This produces ~1km pixel SST maps accurate to 0.1°C. The SST images were interpreted on the basis that warmer water is dynamically higher than cooler water thus promoting movement down thermal gradients with Coriolis effects deflecting the flow to the left.

Since late 1997, Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite data has provided estimates of chlorophyll-a concentration at a ~1km pixel resolution on a daily basis (cloud depending). A series of six images were obtained from CSIRO archives for the 1-23 January 1998 period. Chlorophyll-a estimates from images was calibrated to in-situ measurements taken during the event at the Port Hacking long-term stations.

In situ event sampling

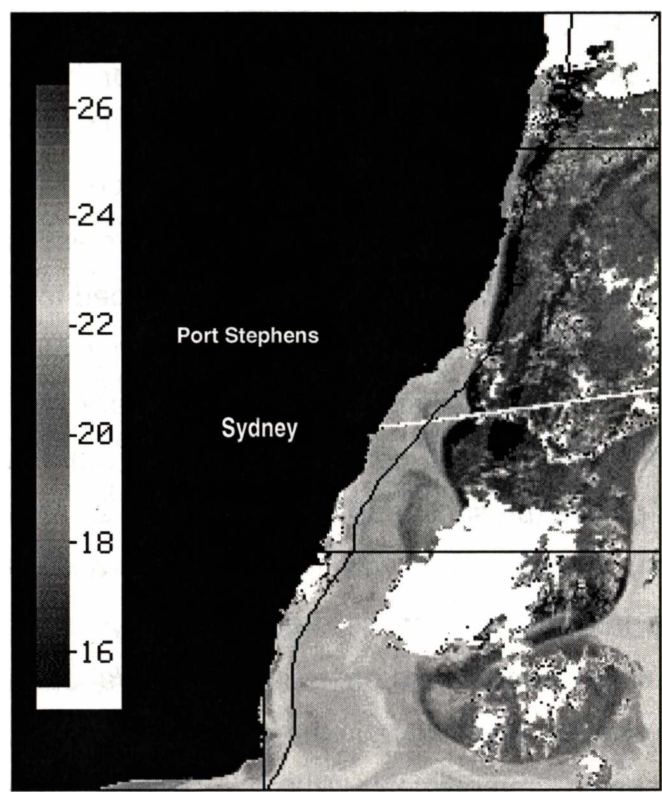
Sampling was undertaken at long term monitoring stations off Port Hacking, on the east-Australian seaboard. The stations located at ~50m (PH50) and 100m (PH100) contours have been monitored by the CSIRO Marine Laboratories since 1942, and thereby provide reference data against which the anomalous conditions can be gauged. As part of a 12-month study (Ajani et al, 2001) the PH50 and PH100 stations were sampled weekly between April 1997 and April 1998. Eight sampling stations along a 25km shore-normal transect complemented the weekly inshore sampling during the peak of the bloom event on 8, 13, 15, 20 and 22 Jan 1998.

A SEABIRD Electronics Sealogger (SBE25 Conductivity, Temperature and Depth Probe-CTD) together with a Chelsea fluorometer (chlorophyll fluorescence) determined continuous profiles through vertical casts. From each cast, water samples were obtained using Niskin bottles (depth depending) at 0, 10, 20, 50, 100, 150, 200 and 5m from the bottom. From each bottle sub-samples were taken for analysis of oxidised nitrogen (APHA Method 4500 - NO₃ F modified; PQL 1 µg/L), ammonia (APHA Method 4500 - NH₃H; PQL 2 µg/L), silica (APHA Method 4500 - Si F modified; PQL 5 µg/L) and reactive phosphorus (APHA Method 4500 - P F; PQL 1 µg/L). A 2L water sample was also collected for chlorophyll-a analysis (APHA Method 10200 H; PQL <2 µg/L, Method Detection limit 0.3 µg/L), to allow cross-calibration of the fluorometer. Nutrient samples were filtered (0.20 µm) within 6 hours of collection and, with exception of silica, frozen at -20°C prior to analysis. Water samples for chlorophyll-a analysis were kept at about 4°C and filtered using a glass fibre vacuum system within 12 hours of collection. After each CTD cast, a 20 µm plankton net haul was made for a qualitative assessment of the dominant algae present at each station. This was dropped to a depth of 50m or less (depending on the depth of water at each station) and vertically hauled through the water column. Algal genera were ranked as dominant (present in every area viewed), common (present in more than six but fewer than 20 areas) or rare (present in up to six out of the 20 areas). At station 4 (PH100 station) phytoplankton was collected with a surface-to-bottom drop of a 35 µm free-fall plankton net haul (HERON, 1982). This sample was used to document overall taxa present (presence/absence) and to quantitatively evaluate species abundance in the overall water column. All net samples were preserved immediately with 3% glutaraldehyde and refrigerated until further examination. All phytoplankton were identified to the lowest possible taxon using a light microscope (maximum magnification X400). Quantitative counts of phytoplankton cells were made using the Lund cell method (LUND et al., 1958).

Results and Discussion

Overview

Intrusions of cool nutrient rich water off Sydney, NSW, periodically occur during the summer season (Jan-April) in response to EAC or wind driven forcing. Time series temperature records on the inner shelf (as recorded by ORS between 1991-98) typically show intrusions of cool water near the sea floor during summer to depths of 40m over a predominant weatherband period of ~ 9 days. The intrusions during January 1998 occurred for 26 days, with maximum penetration to 12m depth on 13 January when temperatures had reduced to 13.5°C.



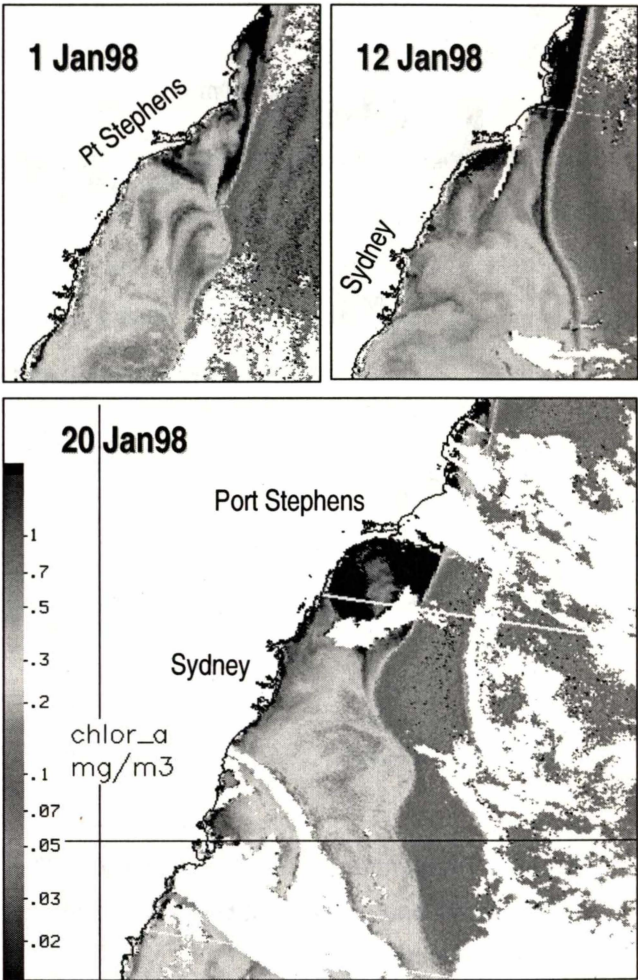
The nutrients associated with this intrusion were at the 99%ile value of oxidised nitrogen and dissolved phosphorous data from long-term PH50 and PH100 records. These comparisons suggest this study captured truly anomalous physico-chemical conditions for the region.

Figure 2. Sea Surface temperature of the Tasman Sea from NOAA14 AVHRR satellite indicates divergence of the East Australian Current from the coast off Port Stephens in January 1998.

Regional assessment

A period of induced EAC activity on the shelf south of Port Stephens was identified in mid January 1998 from the SST imagery (Figure 2). SeaWiFS images during January 1998 indicated a strong front of high chlorophyll-a (>2 µg/L) water developing inshore of the main EAC flow and separating from the shelf off Port Stephens (Figure 3). With the main EAC flow heading offshore a back-eddy, ~80km in diameter, formed inshore in the lee of the Port Stephens encapsulating a pool of high chlorophyll-a water. The EAC flow contracted alongshore trapping the pool for the remainder of January. High chlorophyll-a water leaked out of the back-eddy and was advected to the south along the coast supplying the Sydney region with phytoplankton.

Figure 3. SeaWiFS chlorophyll-a estimates during January 1998 indicate the development of a plankton-rich cyclonic eddy in the lee of Port Stephens.



Thermistor mooring data along a 300km coastal section between Port Stephens and Jervis Bay, provided an assessment of the extent of the upwelling event in the study region. Figure 4 displays temperature profiles for January 1998 at 50m depth at three selected mooring sites (PS03, PH01 and JB05), together with phytoplankton responses determined from the water

sample transects at Port Hacking. Mooring data suggest the cool water intrusion was coherent over the study region and corresponded to enhanced phytoplankton activity approximately one week later.

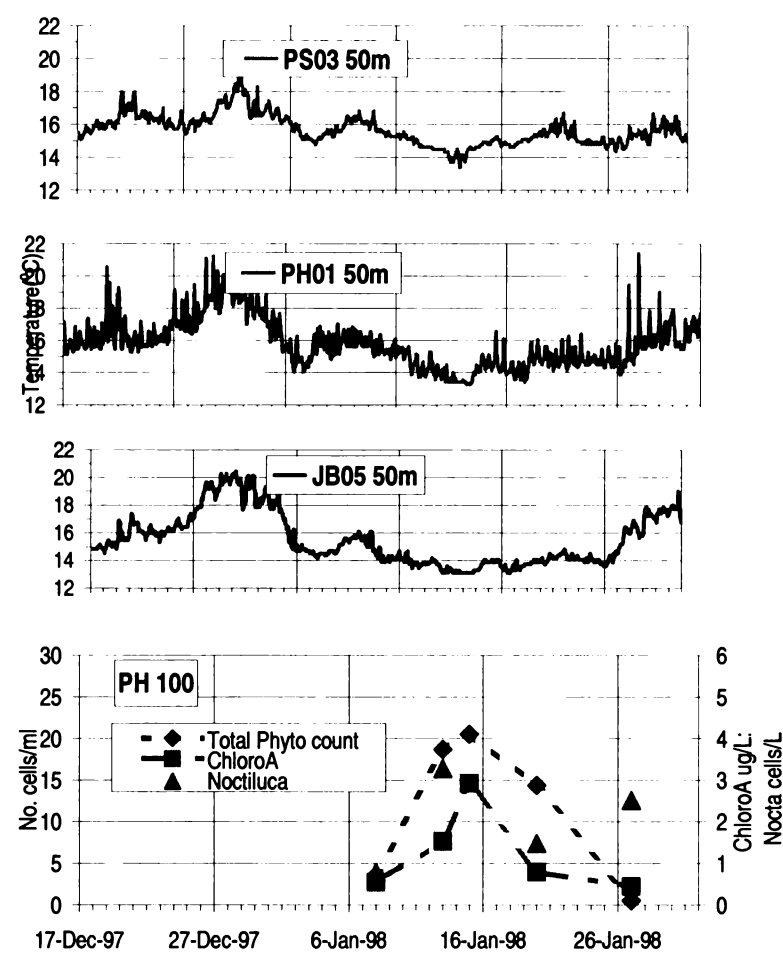


Figure 4. Temperature profiles for January 1998 at 50m depth at three selected mooring sites (PS03, PH01 and JB05), together with phytoplankton responses determined from the water sample transects.

Physico-chemical patterns

Figure 5 shows concurrent wind, current and temperature data recorded at the ORS, together with bottom water temperature record (50m) from the PH01 mooring for the 4-month period from 1/12/97-1/4/99. A cursory look at

the results suggest the intrusion was related to a series of wind induced upwellings in early and mid January 1998.

During the major cool water intrusion seen at PH01, positive correlations exist at the ORS between the alongshore components of the wind, 15m current and both top and bottom temperature records. The intrusion is well related to a period of upwelling favourable winds occurring between 27/12/97 and 16/1/98 and southward flowing currents. Lags of ~24 hours are seen between the southward (negative wind and 15m current components. This lag increases to ~48 hours when comparing the correlated alongshore wind and bottom temperature at PH01. The phase shift for these correlated parameters are given in more detail through coherence and phase spectral analysis. Investigations in the time series temperature records during the December-January period (17/12/97-1/2/98) were conducted according to analysis procedures in Emery and Thomson (1997) and coherence and phase spectra were calculated between selected thermistor moorings for 50m depths.

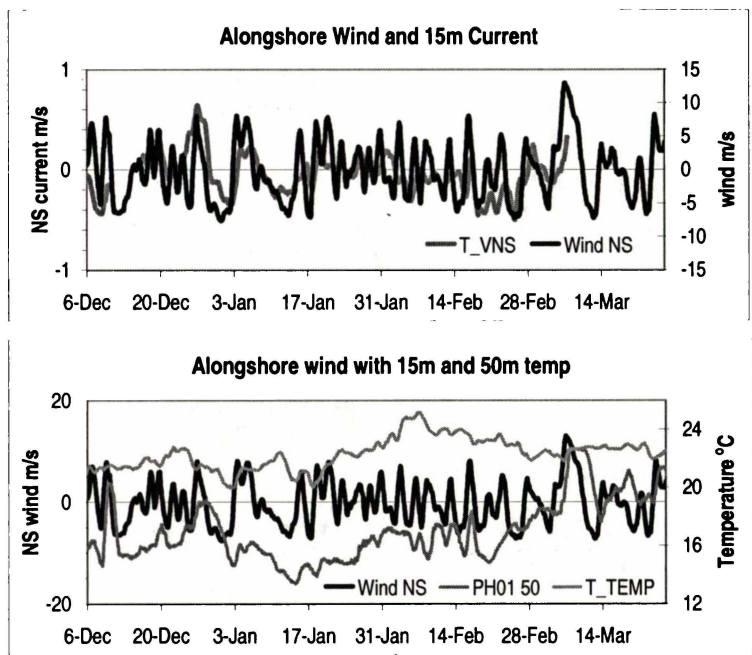


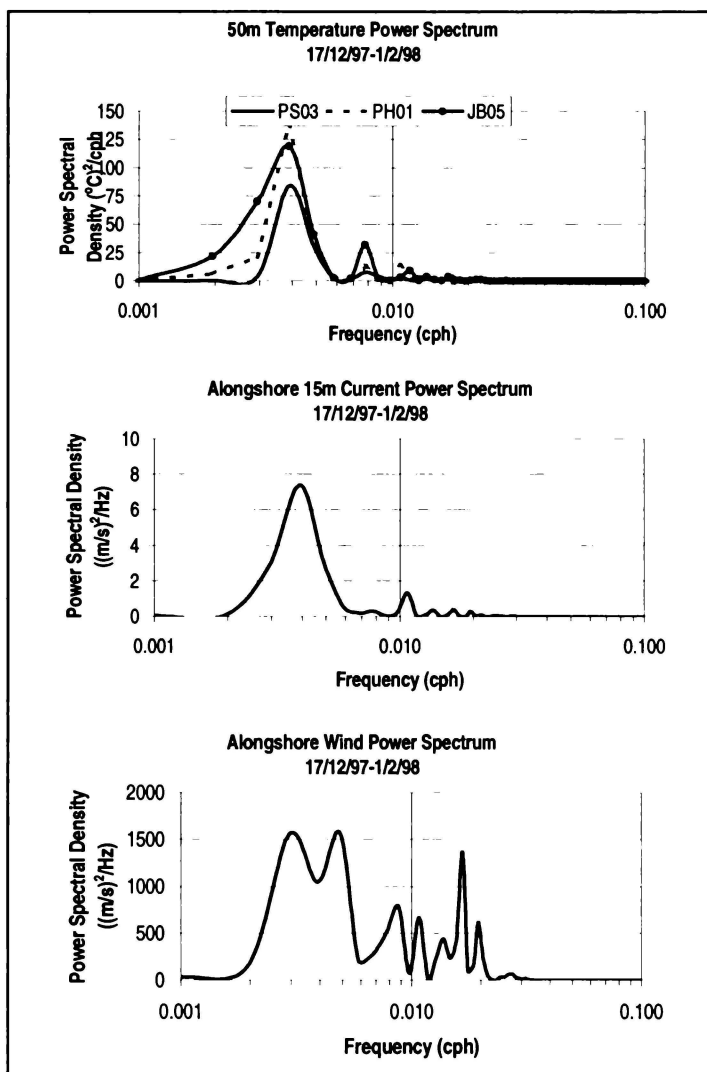
Figure 5. Concurrent surface wind (Wind NS), current (T_VNS) and temperature (T-TEMP) data recorded at the ORS, together with bottom water temperature records (50m) off Port Hacking (PH01 50).

Strong coherency (average $\text{coh}^2=0.9$) was apparent between temperature time series at PH01, ORS, PS03, and JB05 for periods ≥ 5 days, with little phase lag evident within this band (as the records in Figure 4 suggest), indicating the slope-water influence between Port Stephens and Jervis Bay was unanimous.

Results from Fourier analysis conducted on the 50m temperature time series are illustrated in Figure 6, demonstrating that at PS03, PH01 and JB05, a singular spectral peak was pronounced at ~ 10.7 days, re-affirming the similarity between the three locations along the coast during this period.

Figure 6 also displays power spectra calculated for the alongshore 15m current and alongshore wind vector. Peaks were again obtained at the 10-day time period for both parameters, with the wind power spectrum also displaying a secondary peak occurring at the shorter 2.5-day return period.

Figure 6. Power spectra for alongshore thermistor records at Port Stephens (PS03), Port Hacking (PH01) and Jervis Bay (JB05), and alongshore components of wind and 15m depth current at the ORS.



Coherence and phase spectra were also calculated between the forcing variables such as wind and currents, and the bottom temperature record at

PH01 (50m). Unfortunately there was no bottom current meter data available from the ORS during this period, to further examine the alongshore current/temperature relationship.

A strong relationship can be seen in Figure 7 between alongshore 15m ORS current and 50m temperature at site PH01 between $4e^{-3}$ and $1.5e^{-2}$ cycles per hour (cph) (3-10 days), with peaks identified at 3.8 and 8.3 days.

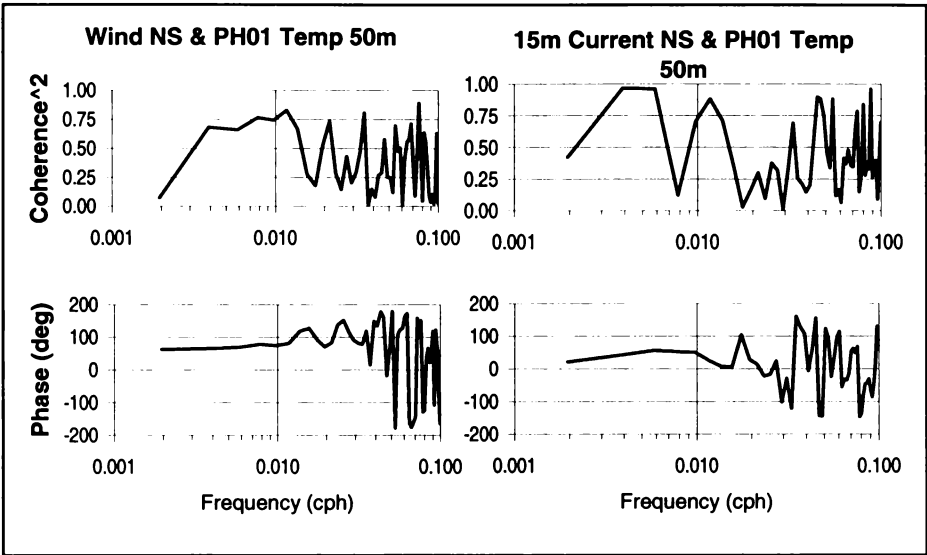


Figure 7. Coherence and phase spectra for correlated ORS alongshore wind and currents, and PH01 50m temperatures.

Stronger coherence (peaks at $\text{coh}^2=0.97$ and 0.88) was obtained between temperature and the alongshore current as opposed to the cross-shelf current (maximum $\text{coh}^2=0.80$). The phase difference was similar for both flow directions, at approximately 45 degrees within the above frequency range. This phase lag (current to temperature) corresponds to ~24 hours for the peak 8.3 day cycle. Similar results were also obtained between the alongshore (N-S) wind component and the 50m temperature record at PH01 (Figure 7), with the same 3-10 day temporal band demonstrating high coherence between the two parameters, together with a lag of approximately 80 degrees (42hrs for the main spectral peak). This indicates predominant wind forcing driving the cool water intrusion during the January 1998 event,

with expected lags for current spin-up and resultant cooler water appearing inshore.

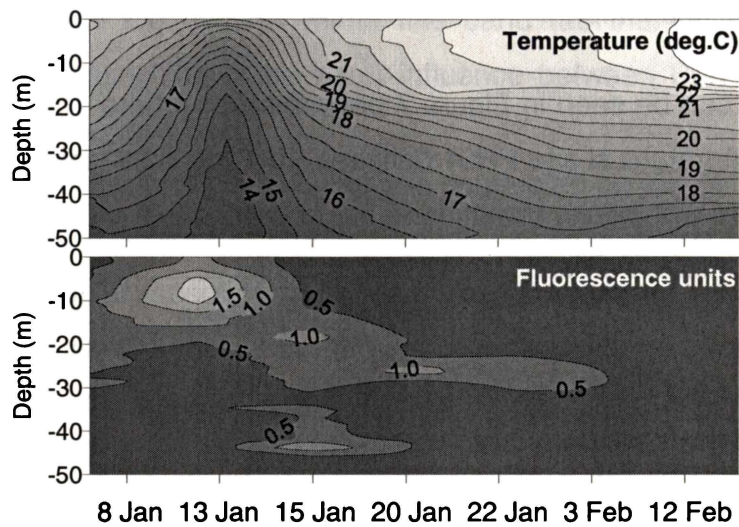


Figure 8: Contoured time series CTD data at PH50 site for temperature and fluorescence during January 1998.

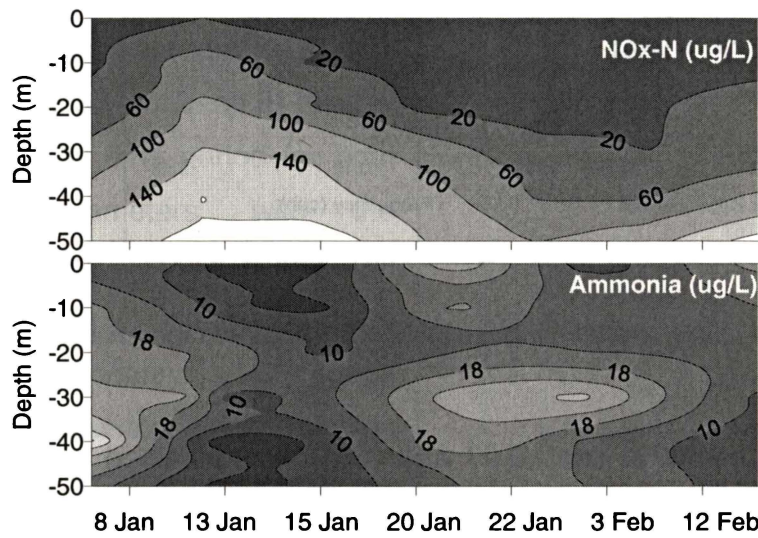


Figure 9: Contoured time series nutrient sampling at PH50 site for nitrate and ammonia (NH₃) during the bloom event in January – February 1998.

The series of contoured nutrient transect profiles, characterised by nitrate and ammonia, are shown with temperature and fluorescence in Figures 8 and 9 from the PH50 sampling station. Conditions were coherent with results at the PH100 station. Patterns of Silica and FRP nutrients were similar to displayed nitrate results. Data indicates that peak nutrient concentrations and fluorescence levels coincide with the peak intrusion event. Ammonia however exhibited a lagged peak at depth, associated with trace fluorescence after the main bloom event.

Temperature and oxidised nitrogen throughout the upwelling period along a shore-normal transect are provided in Figure 10, to characterise the cross-shelf features of this upwelling event that led to extensive visible blooms within the Port Hacking region. The intrusion entered the region in early January 1998, peaking around 13-15th, and slowly abating to the end of the month. At the peak of the upwelling, dissolved nitrogen ($\text{NO}_x\text{-N}$ 140-220 $\mu\text{g/L}$) and phosphorous (FRP 28-34 $\mu\text{g/L}$) levels were well in excess of the prescribed slope-water criteria from HUMPHREY (1960) and NEWELL

(1966). These levels accounted for the upper ~1% of all nutrient concentrations previously measured at the CSIRO stations since 1942. In the vicinity of the thermocline the $\text{NO}_x\text{-N}$ and FRP levels had reduced to 70-140 $\mu\text{g/L}$ and 12-24 $\mu\text{g/L}$ respectively by late January.

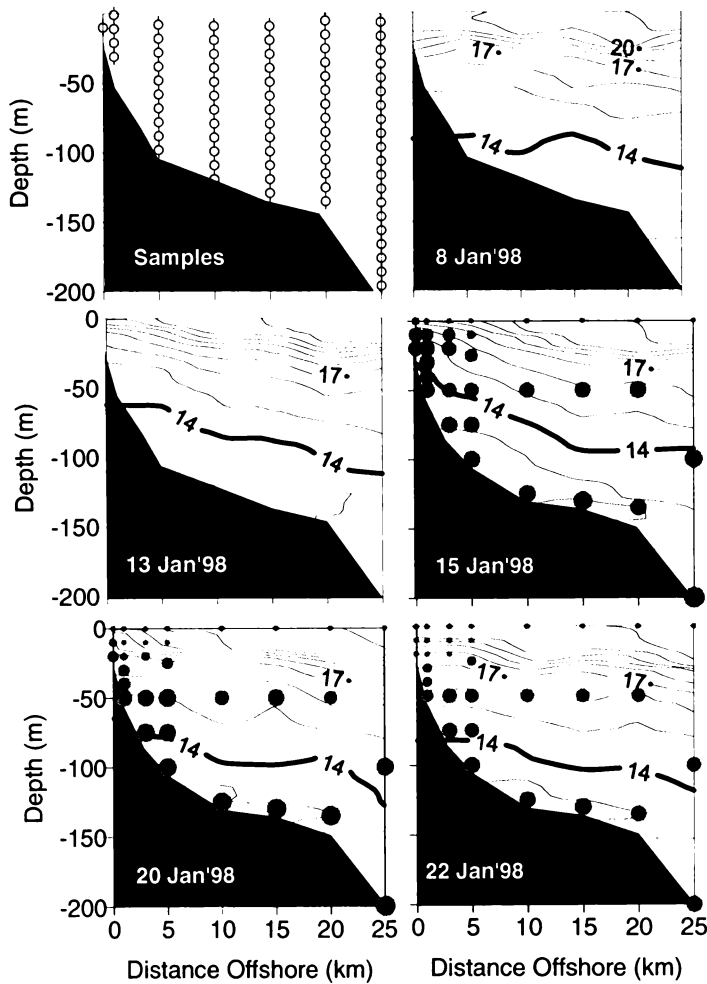
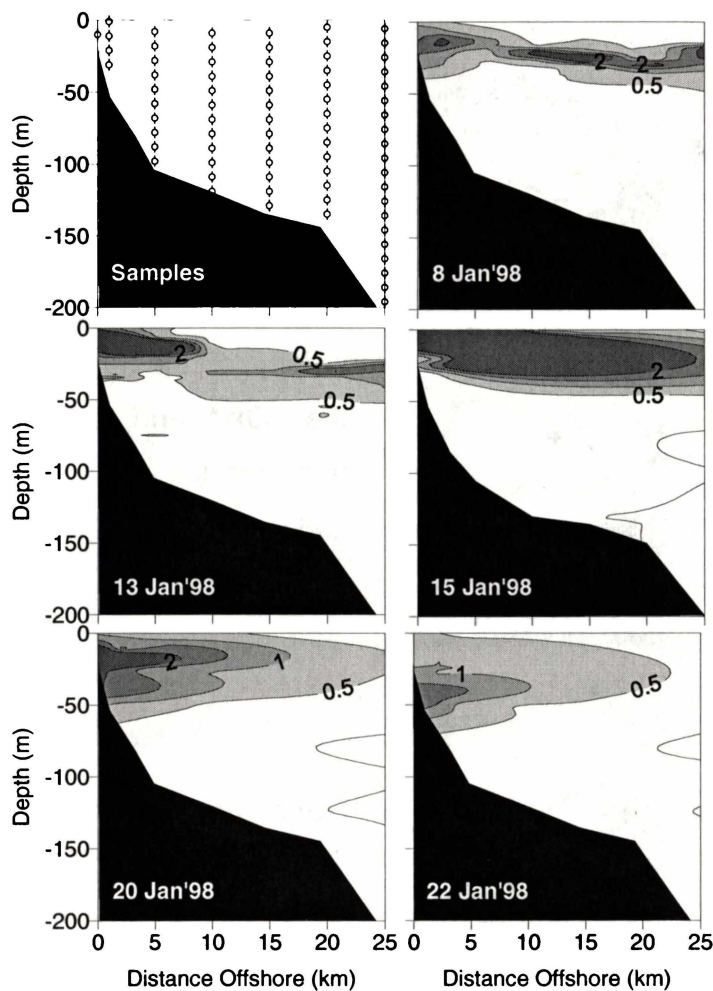


Figure 10: Temperature and associated oxidised nitrogen (as grey dots 0-300 $\mu\text{g/L}$) sampling taken offshore from Port Hacking during January 1998.

Algal Response

Fluorometer profiles calibrated against the Chlorophyll-a sampling are contoured in Figure 11 during the upwelling event. The data suggest an initial supply that was focussed at the coast and shelfbreak before the bloom flooded the upper layer, later contracting to the coast by the end of the peak activity period. The peak chlorophyll-a levels (up to 9 µg/L) that were situated above the thermocline in mid-January, sank to 40m from a near surface expression



as the isotherms flattened. This sinking chlorophyll-a peak (at reduced concentrations) showed a strong association with increasing ammonia levels in Figures 8 and 9, suggestive of planktonic decay. This upwelling event was characterised by a succession of summer bloom species as shown in Table 1.

Figure 11: Chlorophyll-a biomass during an upwelling event at the 50 and 100m stations off Port Hacking.

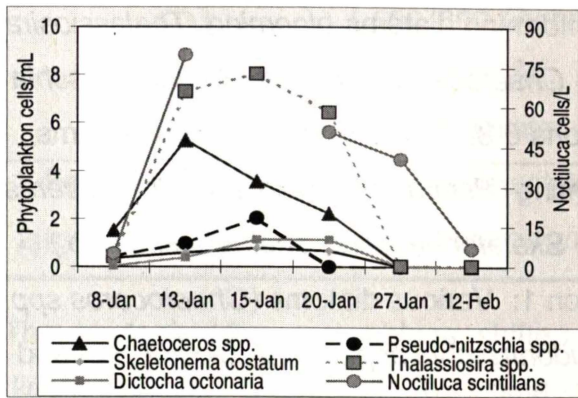


Figure 12: Population densities of the dominant bloom taxa during an upwelling event at Port Hacking Jan-Feb 1998 (0-100m net haul).

Table 1. Summary of Phytoplankton Responses during an upwelling event at Port Hacking (20 μ m net haul to 50m)

Sampling Date Max Chl-a	Max. total cells/L	Dominant Genera (in order of dominance)
29 Dec-97 <1 μ g/L	NA	Large dinoflagellates (<i>Ceratium spp.</i> , <i>Prorocentrum spp.</i> and <i>Protooperidium spp.</i>)
8-Jan-98 1 μ g/L	3.6 x 10 ³	Chainforming diatoms (<i>Chaetoceros spp.</i> , <i>Pseudo-nitzschia spp.</i> , <i>Skeletonema spp.</i> and <i>Thalassiosira spp.</i>) and large dinoflagellates (<i>Ceratium spp.</i> and <i>Protooperidium spp.</i>) present.
13-Jan-98 6 μ g/L	1.9 x 10 ⁴	Various chainforming diatoms blooming (<i>Thalassiosira spp.</i> , <i>Chaetoceros spp.</i> and <i>Pseudo-nitzschia spp.</i>)
15-Jan-98 9 μ g/L	2.0 x 10 ⁴	Stations 1-4: Various chainforming diatoms blooming (<i>Skeletonema costatum</i> , <i>Chaetoceros spp.</i> , <i>Thalassiosira spp.</i> and <i>Pseudo-nitzschia spp.</i>) Station 5: <i>Dictyocha octonaria</i> and various

		chainforming diatoms <i>blooming</i> (<i>Thalassiosira</i> spp., <i>Chaetoceros</i> spp. and <i>Pseudo-nitzschia</i> spp.) Stations 6-8: Various chainforming diatoms <i>blooming</i> (<i>Pseudo-nitzschia</i> spp. <i>Chaetoceros</i> spp., <i>Skeletonema</i> and <i>Thalassiosira</i> spp.)
20-Jan-98 3µg/L	1.4 x 10⁴	Station 1: Various diatoms (<i>Chaetoceros</i> spp., <i>Pseudonitzschia</i> spp., <i>Thalassiosira</i> spp. and <i>Skeletonema</i> sp.) Stations 2-4: Less of the above diatom species with <i>Noctiluca scintillans</i> increasing. Station 5: Diatoms (<i>Pseudo-nitzschia</i> spp.) Station 6: Diatoms (<i>Thalassiosira</i> spp., and <i>Pseudonitzschia</i> spp.) Stations 7-8: <i>Pseudonitzschia</i> spp. <i>blooming</i>, large dinoflagellates (<i>Ceratium</i> spp., <i>Dinophysis</i> spp., <i>Pyrocystis</i>) and the silicoflagellate <i>Dictyocha speculum</i>.
22-Jan-98 1µg/L	NA	Stations 1-3: <i>Noctiluca scintillans</i> and <i>Cerataulina</i> sp. Blooming Stations 4-7: <i>Noctiluca scintillans</i> and <i>Leptocylindrus</i> sp. Blooming. Other species present include <i>Rhizoselenia</i> spp., <i>Ceratium</i> spp., <i>Pyrocystis</i> spp., Station 8: <i>Pseudo-nitzschia</i> spp and <i>Noctiluca scintillans</i>.
27-Jan-98 <1µg/L	5 x 10²	<i>Noctiluca scintillans</i> blooming; other diatoms <i>Pleurosigma</i> sp. and <i>Leptocylindrus</i> sp. present.
29-Jan-98 <1µg/L	NA	Stations 1&2: <i>Noctiluca scintillans</i> blooming, other dinoflagellates (<i>Ceratium</i> spp., <i>Protoperidinium</i> spp., <i>Dinophysis</i> spp., <i>Pyrocystis</i>

		<i>spp.</i> and <i>Gymnodinium spp.</i>) present. Stations 4&5: <i>Noctiluca</i> decreasing. Large dinoflagellates present.
3-Feb-98 2µg/L	NA	<i>Noctiluca scintillans</i> ; other large dinoflagellates and <i>Pleurosigma sp.</i> present.

The phytoplankton assemblage shifted from a background level of large dinoflagellates, typical of this time of year (maximum chlorophyll-a concentration of <1 µg/L), to a blooming of chain-forming diatoms (dominant species being *Chaetoceros spp.*, *Skeletonema costatum*, *Pseudo-nitzschia spp.* and most predominantly *Thalassiosira spp.*) with a maximum chlorophyll-a of 9 µg/L on 15 January. Population densities of each of these dominant bloom taxa are shown in Figure 12.

Whilst *Noctiluca scintillans* cell concentrations peaked on 13 January 1998, visible *Noctiluca* blooms (“red tide”) were subsequently recorded from 22 January through until late February. At this time the photosynthetic phytoplankton activity diminished (chlorophyll-a <1 µg/L) and the community once again returned to relatively low numbers, dominated by dinoflagellates and other nanoplankton, typical for this time of year (HALLEGRAEFF, 1981). Species diversity ranged from 23 taxa to 40 with the maximum diversity being apparent on 20 January 1998. Figure 12 shows the shift in phytoplankton community composition during the upwelling event. Low cell concentrations are apparent prior to the upwelling with diatoms being the phytoplankton taxa which most quickly respond to the increase in nutrient availability characteristic of slope water intrusions.

Conclusions

A remote phytoplankton source in Sydney coastal waters was suggested by MURRAY and SUTHERS (1999) from studies undertaken concurrently at Sydney and Port Stephens during an upwelling event in early January 1997. Large senescent *Noctiluca* cells were predominant in Sydney waters, whereas at the Port Stephens location the population was dominated by smaller actively feeding cells. From this event and previous ones off Sydney the smaller actively feeding cells were correlated to high chlorophyll-a levels, whereas the larger senescent cells corresponded to low chlorophyll-a concentrations. The SeaWiFS imagery during January 1998 confirms that a remote source of phytoplankton from a recirculating eddy in the lee of Port Stephens appears to be feeding southward to Sydney's coastal waters.

The instantaneous nature of the bloom coinciding with the cool-water intrusion, contrary to the usually observed incubation lag period, indicates populations had already been enhanced and advected alongshore to the Sydney region, as both the SeaWiFS imagery and MURRAY and SUTHERS (1999) suggest. The upwellings predominantly driven by wind events in January, were complemented by alongshore flow from the EAC. Thus the plankton streaming into the Sydney region, were further enhanced by slope-water nutrient supplies, allowing extensive blooms to prevail through to mid February 1998 as observed from Port Stephens to Jervis Bay.

On a more regional scale SST imagery indicated that an anomalous warm pool was present off the NSW coast in January 1998,

with respect to averaged conditions. This contracted to the east across the Tasman and was present off the NZ east-coast in February-March 1998 (MURPHY and UDDSTROM, 1998). In both cases they were associated with anomalously cooler inshore waters and widespread algal blooms. This warm anomaly was associated with the breakdown of the 1997 ENSO event.

Curiously similar strong summer upwellings were experienced at the end of the 1992 ENSO, which coincided with large scale phytoplankton activity off the NSW coast (and in particular Jervis Bay), and the NE coast of New Zealand (LEE et al., 1996). Effects of ENSO on the NSW coastal climatology and its influence on the plankton community, is developed further in LEE et al. (2001).

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6-3 PHYTOPLANKTON DYNAMICS AT A LONG-TERM COASTAL STATION OFF SYDNEY, AUSTRALIA

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Running Head: Phytoplankton patterns at CSIRO's long-term station off Sydney.

Abstract

Phytoplankton assemblages and their physicochemical environment were investigated during 1997-98 at a marine long-term coastal monitoring station off Sydney, Australia, and compared to those previously seen at this location. Phytoplankton blooms (significant population increases) coincided with episodic slope water intrusions (upwelling/uplifting) lasting 2-22 days and occurring from September to February. These blooms appeared to occur in response to slope water intrusions. The hydrological forcing variables of bottom- and surface-water nutrients and temperature, (including time-lagged data), were identified using Principal Component Analysis as those variables that explained 60% of the variability of the total phytoplankton biomass throughout the year.

Phytoplankton blooms of similar frequency and magnitude to those seen in this study have been previously recorded. However, in contrast to earlier work, where a variety of taxa dominated throughout the year, the small diatom *Thalassiosira partheneia* generally dominated blooms in this study. In addition, presence/absence data for the heterotrophic dinoflagellate, *Noctiluca scintillans*, indicated a higher frequency of occurrence for this species than previously documented. *N. scintillans* was observed in 61% of samples collected throughout the year, being absent from only a few samples in the autumn and winter months. It is hypothesised that the shift in dominance from previously recorded bloom species to *Thalassiosira* could be a contributing factor to the increase in *N. scintillans* (a favoured food source by *N. scintillans*) in NSW coastal waters. The reason for the recent dominance of these particular phytoplankters is unclear but may be related to physicochemical conditions such as a decrease in phosphate and oxidised nitrogen concentrations and warmer water temperatures experienced during our sampling period compared to previous years.

A phytoplankton inventory is included as an Appendix. This includes what appears to be the first record of the potentially toxic diatom

Pseudonitzschia australis in Australian waters and the first record of the harmless diatom *Pleurosigma chilensis* since its “type” description from the coastal waters of Southern Chile, 1941.

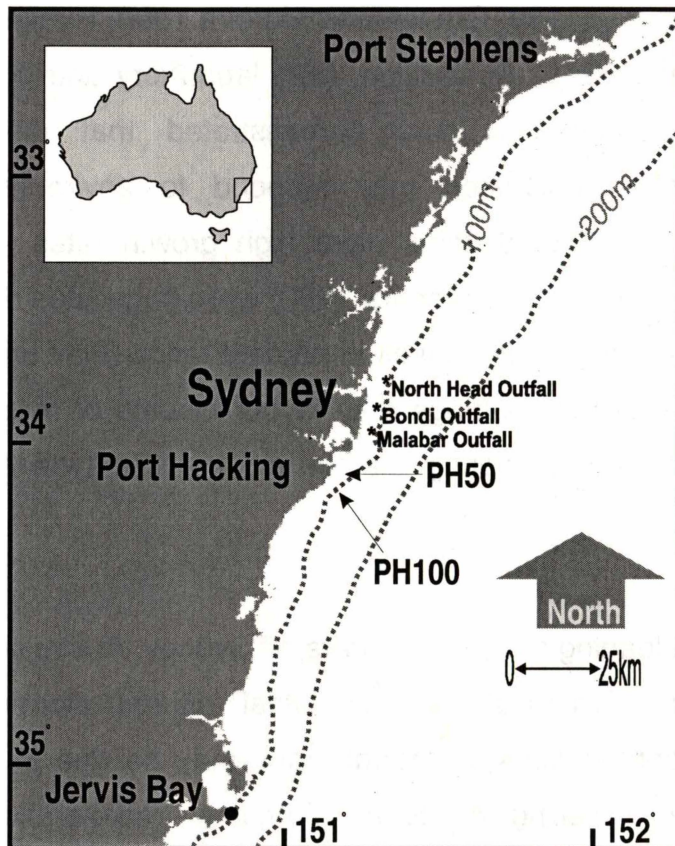
Index Words: New South Wales, algal blooms, nutrients, *Noctiluca scintillans*, *Thalassiosira partheneia*.

Introduction

Eutrophication in coastal marine waters is recognised as a worldwide and growing problem (Smayda 1990) leading to enhanced phytoplankton growth (including nuisance and/or toxic algal blooms) or a change in the species composition of phytoplankton and other organisms. Various studies have demonstrated a direct link between increasing eutrophication and/or shifts in nutrient ratios with respect to phytoplankton composition and abundance (Oviatt et al. 1989, Graneli and Moreira 1990, Riegman et al. 1992, Pan and Rao 1997). In addition, both laboratory and coastal marine mesocosm experiments have demonstrated that different taxonomic groups of phytoplankton may respond to environmental variables in different ways eg. diatoms have high growth rates under nutrient rich-conditions (Graneli and Moreira 1990) while flagellates do not (Oviatt et al. 1989). In addition, decreases in nutrient ratios (Si:N or Si:P) due to increases in N- and P- loadings may favour blooms of nuisance flagellate species over normal spring diatom blooms (Smayda 1990, Sommer 1994).

Anthropogenic nutrient loading to coastal waters off Sydney, Australia, is a result of the discharge of domestic and industrial effluent, stormwater runoff and estuarine contributions. 'Natural input' may be due to wind and/or current driven upwelling of ocean nutrients, regeneration of nutrients in coastal sediments and natural fixation of atmospheric nitrogen. Between September 1990 and July 1991, Sydney's three major deep ocean outfalls (at Malabar, Northhead and Bondi) were commissioned, diverting most of Sydney's sewage (80%) from cliff-face to deepwater outfalls (Figure 1). In a final assessment of the performance of these outfalls, it was recognised that the possible nutrient enrichment of Sydney's coastal waters and its effect on phytoplankton growth (algal blooms), is an issue warranting further investigation (Pritchard et al. 1996).

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has collected data at two stations offshore from Port Hacking (50 m and 100 m station) since the 1940's. Studies at these stations have included variations in plankton pigments (Humphrey 1960, 1963, Hallegraeff 1981), water quality parameters (Newell 1966) and their relationship with phytoplankton abundance (Grant and Kerr 1970, Grant 1971), and the seasonal succession of phytoplankton in relation to the



hydrological environment (Jeffrey and Carpenter 1974, Hallegraeff and Reid 1986). The long-term variability of the oceanographic data at the Port Hacking stations has been summarised by Sydney Water (Water Board 1988b) and was discussed by Hahn et al. (1977) and Hallegraeff (1993b).

Figure 1. Study location for phytoplankton sampling.

Hallegraeff (1993b) suggested that nitrate and phosphate concentrations had increased at these stations between 1960 and 1990. Similarly, he noted that there has been an apparent increase in the frequency, strength and extent of visible algal blooms between 1984 and 1993, with only a handful reported prior to this time. Hallegraeff and Reid (1986) investigated phytoplankton species successions at the 100m station in relation to physicochemical factors and confirmed the species sequence found by previous investigations. At present, the CSIRO continues to monitor physicochemical parameters at the 100m station, however, there

has been no detailed investigation into phytoplankton composition and seasonal successions since the weekly sampling from 1978 to 1979 (Hallegraeff and Reid, 1986).

This paper is one component of a three-year ocean nutrient study to characterise ambient nutrient concentrations and more specifically, to identify the relative significance of various sources of nutrients in New South Wales coastal waters. In particular, the study is focusing on the extent and associated nutrient concentrations of slope water intrusions and upwellings, so that this information can be compared with anthropogenic and estuarine discharges and related to phytoplankton growth at various locations along the coast of New South Wales, Australia.

Methods

Study Location and Sampling Design

Weekly sampling took place at the long term 100 m CSIRO monitoring station (34° 05'30"S., 151°15'30"E.) offshore from Port Hacking for a period of one year beginning in April 1997 (Figure 1). A SEABIRD Electronics Sealogger (BE25 Conductivity/Temperature/Depth Probe-CTD) was employed to measure physicochemical variables (depth, temperature and salinity). On the same cast as for the CTD, 5 litre Niskin bottles were attached at various depths (0, 10, 25, 50, 75 and 100m). From each Niskin bottle, water samples were analysed to determine concentration of oxidised nitrogen (nitrate + nitrite), ammonia, phosphate (dissolved reactive phosphorus), silicate (dissolved reactive silicate) and chlorophyll a. After each CTD cast, a 35 μ m free-fall plankton net haul (Heron 1982) was collected from a depth of 100 m and the types and abundance of algae that were collected were determined.

Nutrients and Chlorophyll a

Samples were filtered (within 2 hours of collection) using 0.2 μ m "Mini-sart" disposable filters and the filtrate was divided into a 10mL subsample

for silicate analysis and a 30mL subsample for phosphate, ammonia and oxidised nitrogen analyses. The silicate samples were stored in the dark at room temperature, while the remaining nutrient samples were stored frozen (-20 °C) before dispatch to the EPA chemical laboratory. The methods used for nutrient analyses and detection limits are given in Table 1. Chlorophyll a was collected from the water samples on a glass fibre filter using a vacuum filtering system. These filter papers were then wrapped in foil, labelled and stored frozen (-20°C) until chlorophyll a determination was undertaken (American Public Health Association Method {APHA} 10200 H, Practical Quantitation Limit = 1 µg/L, Method Detection Limit = 0.3 µg/L).

Table 1. The methods used for nutrient analyses and detection limits.

Test ID	Methods used during testing	Units	PQL* (µg/l)
Oxidised Nitrogen	APHA Method 4500 – NO3 F (Modified)	µg NOx-N /L	1
Ammonia	APHA Method 4500 – NH3 H	µg NH ₃ -N /L	2
Dissolved Reactive Phosphorus	APHA Method 4500 – P F	µg PO ₄ -P /L	1
Dissolved Reactive Silicate	APHA Method 4500 – Si F (Modified)	µg SiO ₂ /L	5

*Practical Quantitation Limit

Phytoplankton Identification and Enumeration

Algal samples were preserved with 3% glutaraldehyde (final concentration) immediately after collection and refrigerated until further investigation. All phytoplankton were identified to the lowest possible taxon using a light microscope (maximum magnification X400).

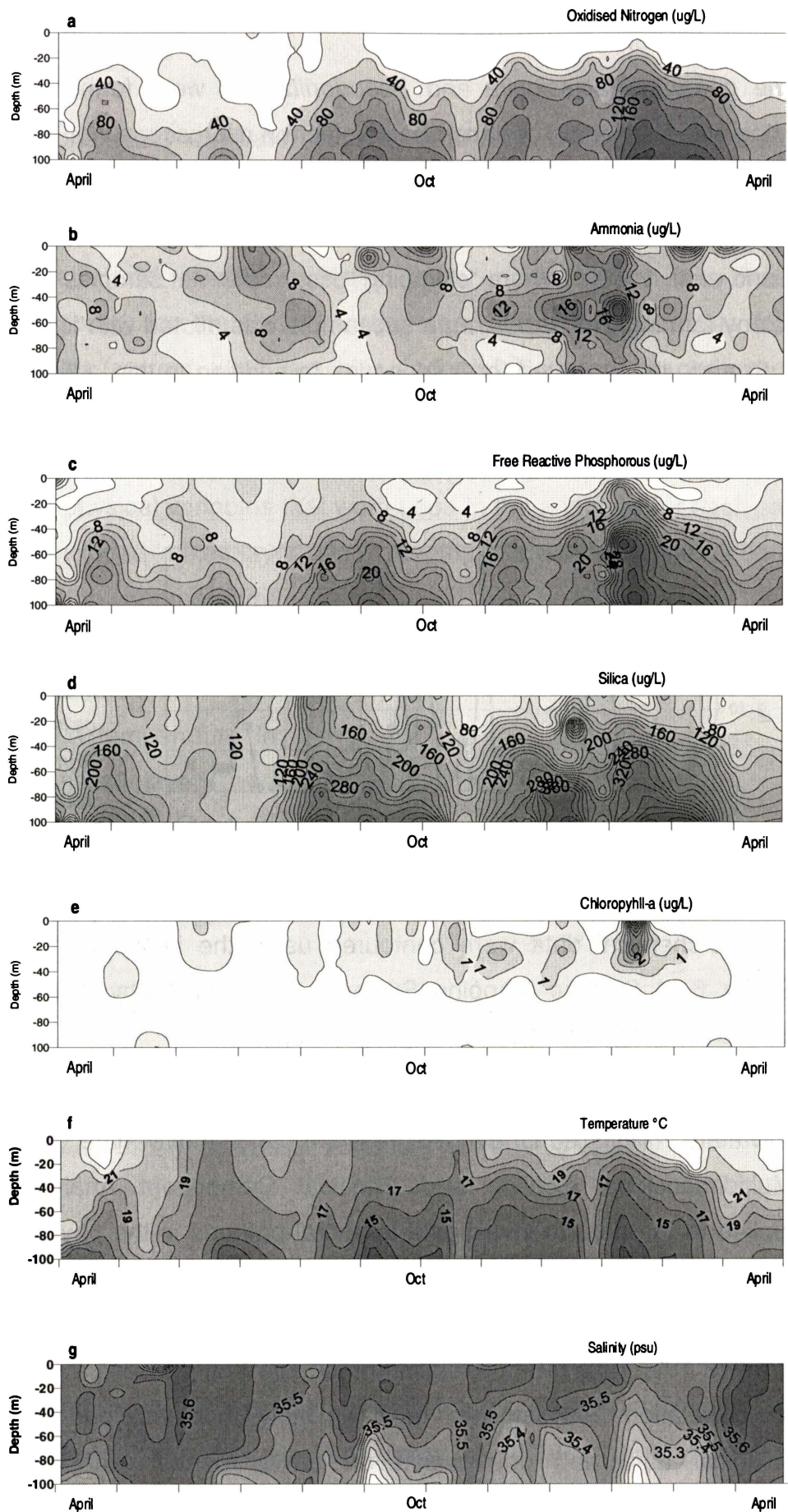


Figure 2a-g. Contour maps of Port Hacking 100m nutrient and chlorophyll concentrations including temperature and salinity.

The genera *Thalassiosira* and *Pseudonitzschia* were further examined using either scanning or transmission electron microscopy.

Samples were investigated initially for presence/absence of taxa followed by quantitative counts of phytoplankton cells using the Lund cell method (Lund et al. 1958). Where “clumping” occurred in net samples (due to the colony-forming *Thalassiosira*), a subsample was diluted with filtered water (1:8) and ultrasonicated for 8 seconds. In addition to this, 1% “Biosolvin” (mucolytic solution) was added to break down the phytoplankton’s mucilage (R. Casotti unpublished data).

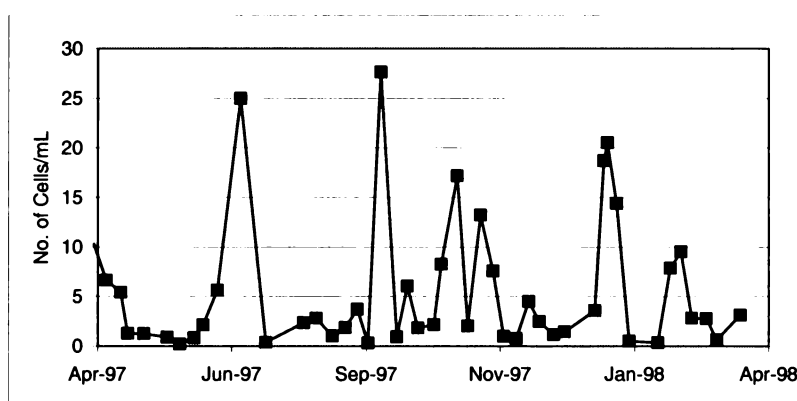


Figure 3. Total number of phytoplankton cells/mL at the Port Hacking 100m station.

Analyses of Data

Physico-chemical data were contoured using the krigging grid method (Surfer 6.01 Surface Mapping System). Continuous physical data was contoured using one meter averaged bin depths.

Univariate (Multiple Linear Regression) and multivariate techniques (Multidimensional Scaling and Principal Component Analysis) were applied to the data to investigate temporal patterns in the phytoplankton, nutrient and physicochemical data sets. A BIOENV procedure (Clarke and Ainsworth 1993, implemented in the PRIMER program, Clarke and Warwick 1994) is a rank correlation procedure that provides a measure of the correlation between two rank similarity matrices, one based on biological data and one based on environmental variables. This procedure was applied to the abundance data to identify the environmental variables that provide the best explanation of the multivariate species composition patterns.

Additional data on water currents and wind strength from the Ocean Reference Station (an instrument string moored 4km east of Bondi in a water depth of 65m) was added to the physical data set. Sunshine (hrs/day) and rainfall (mm/day) data, collected by the Bureau of Meteorology for the Sydney area, were also included. Data for these variables (current, wind, sunshine and rainfall) were averaged over the 48 hours prior to time of sampling on each day to incorporate a measure of exposure to these variables experienced by the phytoplankton community. Other physical variables that were used in the analyses for each sampling date included 'mixed layer depth' (depths of the thermocline as defined by maximum temperature gradient), 'mixed layer temperature' (the average temperature in this mixed layer) and 'degree of stratification' (the temperature difference between 0m and 100m).

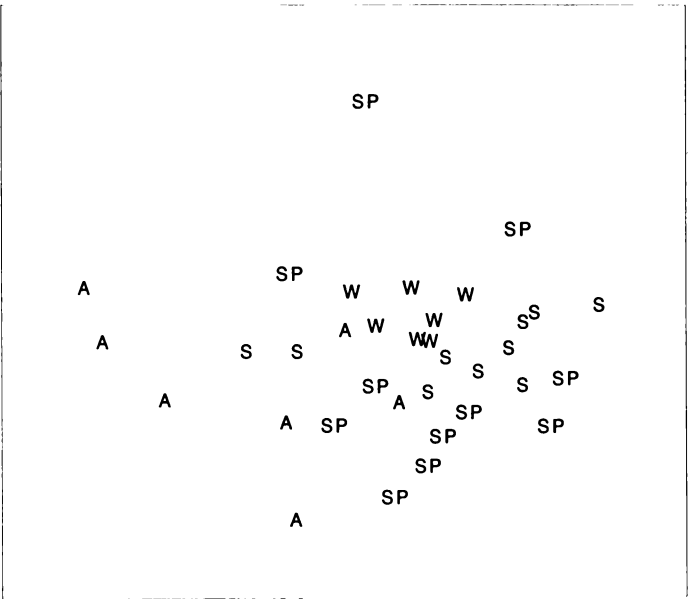


Figure 4. Two-dimensional Multi-dimensional Scaling Ordination for phytoplankton count data (Stress = 0.24). S=Summer, A=Autumn, W=Winter, SP=Spring.

Results

Physicochemical Data

Data was collected for 51 sampling days. Oxidised nitrogen concentrations ranged from <1 - 240 µg/L, ammonia N <1 - 32 µg/L, phosphate-P <1 - 56 µg/L, and silicate (as SiO₂) 34 - 460 µg/L (Figures 2 a-d). Episodic fluctuations occurred in all nutrient concentrations throughout the year, reaching maximum concentrations in the summer months (January to February). Upwelling/uplifting of nutrient-rich water (oxidised nitrogen, phosphate and silicate) onto the shelf occurred

predominantly from spring to late summer (September to February). Ammonia concentrations increased in the summer months when biological activity was at its greatest. This activity is reflected in the annual cycle of chlorophyll *a* concentrations (Figure 2 e). Short-lived peaks of chlorophyll *a* were most prominent in October and January with minor peaks in June, August-September, November-December and February.

Contoured temperature data for the sampling period showed a seasonal cycle of upper layer warming (maximum in February) whilst bottom waters experienced cold water upwellings/upliftings in spring and late summer (Figure 2 f). Notable thermal stratification occurred from November (15 – 20°C) to May (18 – 21°C), peaking in February (13 – 23°C).

No clear seasonal pattern emerges for the contoured salinity data (Figure 2 g). Low variation in surface salinities reflected the low rainfall coinciding with drought conditions associated with the presence of a strong El Niño influence during this year. Major halocline (salinity stratification) periods extended from July to March (spring and summer) with the minimum salinity signal in bottom waters recorded at 35.1 psu (maximum - 35.7 psu in surface waters). These periods were associated with upwellings/upliftings of colder, less saline water onto the coastal shelf. For the remainder of the year the water column appeared well mixed.

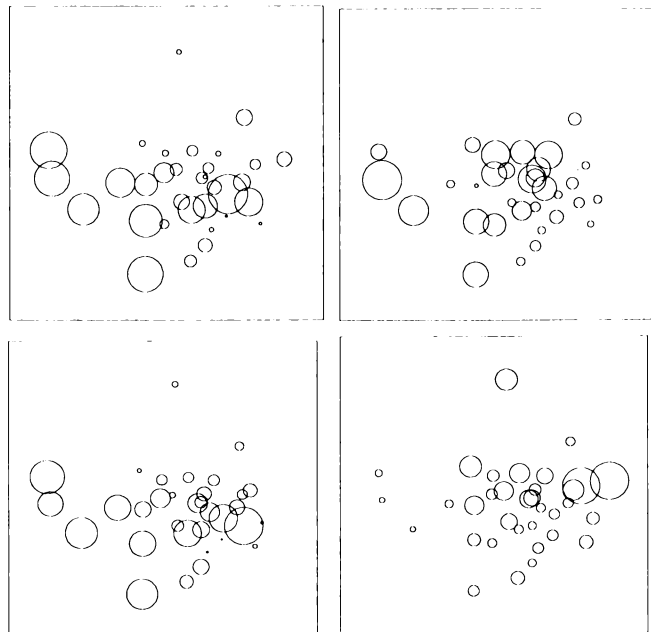
Phytoplankton Identification and Enumeration

A total of 49 sampling times were completed with a total of 110 taxa (60 different genera) identified from the entire sampling program (Appendix 1). The majority of taxa had previously been documented from this station (Hallegraeff and Reid 1986) with the exception of some individual taxa (* Appendix 1). The number of taxa ranged between 14 and 40, with minimum numbers of taxa in December and maximum numbers in May-June. There was an extended period of low phytoplankton diversity between September and November.

Cell densities for each sampling date ranged from <1 to 28 cells/mL (Figure 3). Short-lived (1 to 3 week) monospecific phytoplankton blooms occurred in April (cyanobacterium *Trichodesmium erythraeum*; 9 cells/mL), and in June, September, October, November and January (the small diatom *Thalassiosira* spp.; 25 cells/mL). In February, the chain-forming diatom *Pseudo-nitzschia* spp. dominated the phytoplankton community (6 cells/mL).

Classification analysis using log transformed data from the sampling times based on the similarity of species assemblages resulted in five significant groups. The first group represented the autumn period when phytoplankton productivity was at its lowest. The second and third groups represented times scattered throughout the entire twelve-month period when cell numbers were low. The fourth group was associated with the spring and summer non-bloom periods and the fifth group represented the bloom periods in winter, spring and summer. When seasonal divisions were superimposed on the configuration, autumn sampling dates showed wide scatter, while winter, spring and summer dates clustered closely together. Bloom dates for winter, spring and summer were not clearly distinguished in the ordination (Figure 4).

Figure 5a – d (left to right). Two-dimensional Multi-dimensional Scaling Ordination for phytoplankton count data overlaid with environmental variables. (a. temp 0-25m; b. temp.100m lagged by one week; c. temp 0-25m lagged by one week, d. phosphate 0-25m lagged by one week)



A BIOENV procedure

identified four environmental variables (Table 2) as providing the best explanation of the multivariate species composition pattern based on the

sampling dates (as previously seen in Figure 4). When each variable is superimposed on the abundance configuration, the importance of each variable becomes apparent (ie the size of the circle is proportional to the magnitude of the environmental variable) (Figure 5 a-d).

A reordering of the original data matrix and a corresponding cluster of species according to the similarity of the counts and sampling dates at which they occurred resulted in three major groups (Table 3).

Table 2. Results from BIOENV procedure for phytoplankton composition (count data) and physicochemical data

Best Single Variable	temp 0-25m	r=0.29
Best Two Variables	temp 0-25m, temp 100m lagged*	r=0.39
Best Three Variables	temp 0-25m, temp 100m lagged, temp 0-25m lagged	r=0.39
Best Four Variables	temp 0-25m, temp 100m lagged, temp 0-25m lagged, phosphate 0-25m lagged	r=0.4

*data which has been time-lagged for one week

The first group identified common species (diatoms, five dinoflagellate taxa, a silicoflagellate taxon, unidentified flagellates, raphidophytes and nanoplankton) that occurred throughout the entire year as well as the common spring and summer bloom species. The second group identified the 'infrequently counted' taxa as well as the autumn bloom species, *Trichodesmium erythraeum* and the red tide-forming *Noctiluca scintillans*. The third group represented a 'rarely counted' dinoflagellate group. Population densities of the harmless dominant taxa found throughout the sampling period are shown in Figures 6 a - e. In order of abundance these were *Thalassiosira* spp. *Trichodesmium erythraeum*, *Chaetoceros* spp., *Rhizosolenia* spp., and the diatom combination of *Leptocylindrus* spp. and *Cerataulina* spp. In February 1998, the planktonic diatom *Pleurosigma chilensis* Hustedt & Krasske, began to dominate the phytoplankton community (0.4 cells/mL). The only other previous record of this species is thought to be it's 'type' description in 1941, from the coastal waters of Southern Chile (Krasske 1941).

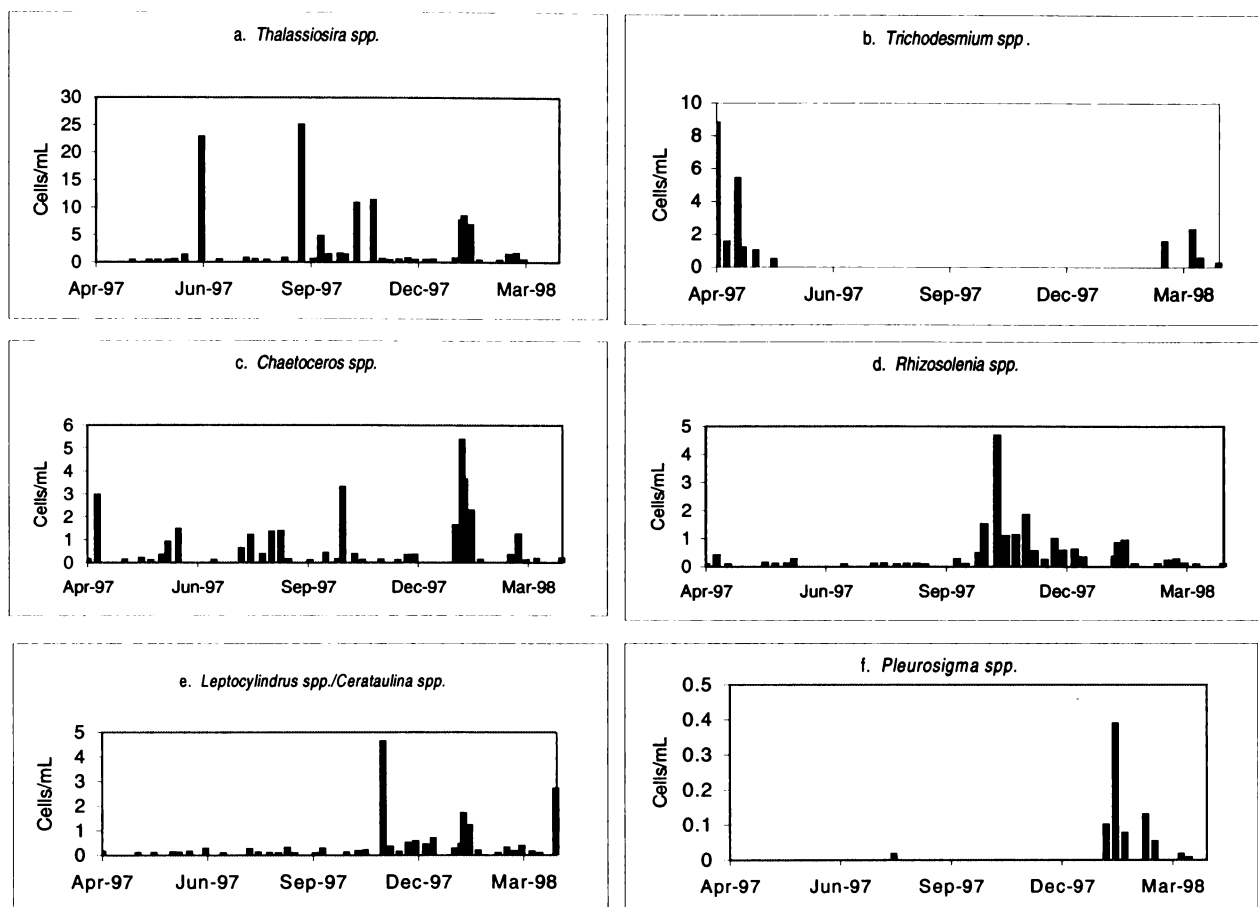


Figure 6a-f. Population densities (0-100m net haul) of the harmless dominant taxa found throughout the sampling period.

Population densities of the potentially harmful taxa *Dinophysis acuminata* and *Pseudo-nitzschia* spp. found throughout the sampling period are shown in Figures 7 a – b respectively. *D. acuminata*, a producer of diarrhetic shellfish poisoning (DSP), showed peak concentrations in January 1998. Species from the genus *Pseudo-nitzschia* spp. have been implicated as the causative organisms of amnesic shellfish poisoning (ASP). They were present throughout the year with greatest numbers in February. Scanning electron microscopy identified two potentially toxic species – *P. australis* and *P. multiseriis* as well as the harmless species *P. pungens*, *P. cf. subfraudulenta*, *P. pseudodelicatissima*, *P. subpacific*a and *P. heimii*.

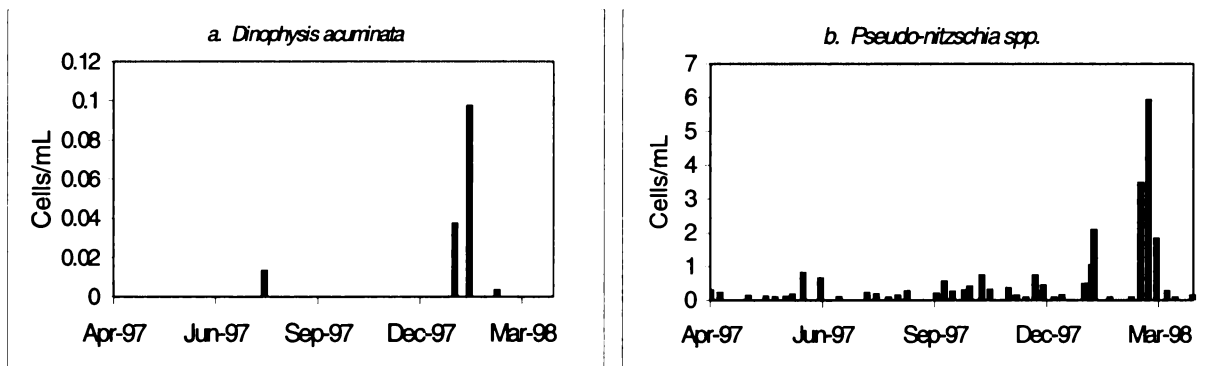


Figure 7a-b. Population densities (0-100m net haul) of the potentially harmful taxa found throughout the sampling period.

Other potentially harmful (some strains) species present throughout the sampling period at this station were *Dinophysis tripos* (present in 27% of samples), *Dinophysis fortii* (6%), *Dinophysis acuta* (2%) and *Prorocentrum lima* (4%). These have all been implicated in diarrhetic shellfish poisoning (DSP) events throughout the world.

The majority of “visual” blooms (causing water discolouration) during the sampling period were dominated by the heterotrophic dinoflagellate, *Noctiluca scintillans*. This species was observed in 61% of samples collected throughout the year, being absent from only a few samples in the autumn and winter months. Other bloom events included *Trichodesmium erythraeum*, *Chaetoceros* sp. and a rarely occurring ‘surf diatom’ *Anaulus australis*.

Table 3. Groups of taxa identified by MDS Classification. Numbers listed represent taxon identification numbers (see Appendix 1).

Group 1	7, 13, 25, 31, 33, 35, 44, 45, 49, 51, 52, 53, 56, 58, 59, 62, 63, 64, 74, 81, 86, 88, 96, 99, 100, 103, 106, 107, 108	Common taxa including spring and summer bloom diatom taxa
Group 2	6, 10, 14, 19, 20, 23, 26, 27, 28, 30, 32, 40, 43, 46, 47, 48, 50, 55, 57, 60, 65, 78, 80, 82, 83, 85, 94, 97, 104, 105	Infrequently counted species including <i>Trichodesmium</i> and <i>Noctiluca</i>
Group 3	29, 48, 68, 72	Rare dinoflagellates

Succession of Spring Bloom Species

The predominant species for this spring sampling period was the diatom *Thalassiosira partheneia*. These blooms began in early September and continued into early November presumably in response to episodic slope water intrusions of cool bottom water (and associated nutrients) being transported onto the shelf. Other genera that became abundant during this period included *Rhizosolenia*, *Chaetoceros*, *Pseudo-nitzschia* and *Eucampia*.

To confirm the major associations found in the spring species successions found by Hallegraeff and Reid in 1986, classification analysis of the 17 most abundant species was performed. Six years of spring data were pooled - five years from previous studies at this location (1971, 1978, 1979, 1980 and 1981) and the data from the present study. Three major associations were revealed (Figure 8). The first association was a group of small chain-forming diatoms present throughout the entire bloom period, the second a group of large centric diatoms, and the third a group of large diatoms and dinoflagellates which appeared towards the end of the spring bloom period. When the present study's succession of bloom species was analysed in isolation, only two major groups were distinguished - a small chain-forming group (which made up the majority of the biomass) and a large diatom and dinoflagellate group. The large centric diatom group, which was previously conspicuous, was scattered throughout these two groups.

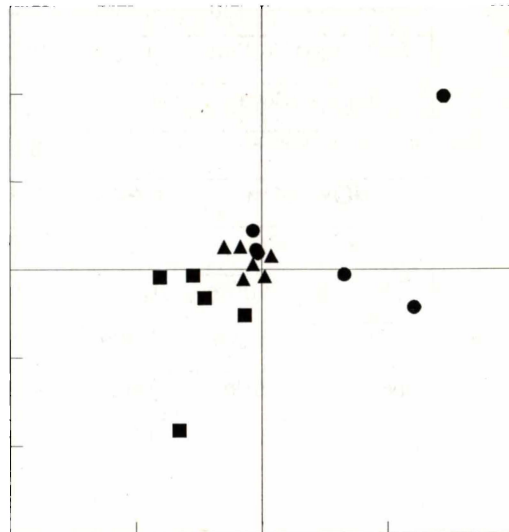


Figure 8. Multidimensional ordination of Bray-Curtis association matrix for spring phytoplankton presence/absence data (Stress=0.11). ▲small diatoms; ■large diatoms; ●large dinoflagellates.

Relationship between the phytoplankton and physicochemical environment

Correlation Analysis using the Pearson Correlation Coefficient was used to identify potential relationships between the total phytoplankton counts and the various physicochemical parameters for each sampling date. In general, significant correlations ($\alpha=0.05$) were found with chlorophyll *a*, temperature and nutrients at various depths. Current, wind, sunshine and rainfall data showed no significant correlations with total phytoplankton counts. Significant correlations, however, were not considered to be causal.

Table 4. A summary of the results from the Principal Components Analysis.

Physicochemical Parameter	Prin 1	Prin 2	Prin 3	Prin 4	Prin 5	Prin 6	Prin 7
Temp 0-25m	-0.063	-0.424	0.191	0.321	0.131	0.097	-0.160
PO ₄ 0-25m	0.101	0.338	0.379	-0.02	-0.303	0.237	0.209
NOx 0-25m	0.106	0.298	0.367	0.088	-0.442	0.001	0.428
SiO ₂ 0-25m	0.081	0.351	0.186	0.317	0.193	-0.354	0.134
Temp_lag1 0-25m	-0.082	-0.366	0.263	0.426	-0.028	0.111	0.137
PO ₄ _lag1 0-25m	0.212	0.263	-0.275	0.178	0.076	0.506	0.069
NOx_lag1 0-25m	0.152	0.224	-0.346	0.365	0.276	0.276	-0.383
SiO ₂ _lag1 0-25m	0.166	0.335	0.001	0.219	0.017	-0.380	0.472
Temp 100m	-0.318	0.000	-0.069	0.489	-0.185	-0.030	0.109
PO ₄ 100m	0.327	-0.057	0.228	-0.06	0.228	0.374	0.408
NOx 100m	0.341	-0.145	0.316	-0.09	0.069	0.087	-0.074
SiO ₂ 100m	0.318	-0.095	0.242	-0.04	0.408	-0.163	-0.333
Temp_lag1 100m	-0.317	0.125	0.345	0.210	0.217	0.127	0.093
PO ₄ _lag 1 100m	0.331	-0.125	-0.075	0.166	-0.442	0.036	-0.058
NOx_lag1 100m	0.323	-0.205	-0.197	0.232	-0.207	-0.078	0.116
SiO ₂ _lag1 100m	0.354	-0.143	-0.089	0.130	0.066	-0.344	0.127

The relationships between selected physicochemical variables (ie. those that demonstrated significant correlations both time-lagged and not time-lagged data) and total phytoplankton counts were then investigated using a Principal Components Analysis (Manly 1991). Data from the surface waters (0-25m) were averaged for each of these variables (as an

integrated average of the euphotic zone). Results from this analysis showed that six principal components were needed before more than 90% of the variability was explained, with the first two principal components explaining approximately 60% of the variation. (Table 4). These first two principal components were the only components that appeared to suggest a straightforward interpretation of the data. The first component was an approximately equalled weighted average of the bottom nutrients and bottom temperature (including the 'time-lagged' data), while the second component was an approximately equalled weighted average of the surface nutrients and temperature (including the 'time-lagged data').

To determine to what degree the patterns observed in the counts may be explained by the physicochemical data, a Multiple Linear Regression analysis was applied to the data. Stepwise regression using backward elimination was used to determine which physicochemical variables had significant associations with the dependent variable, 'total phytoplankton count'. The first and second principal components from the previous analysis were also included in the variables analysed. A variable was included in the model if it was judged to be significant at the $P=0.1$ level.

Table 5. Results of the multiple regression analysis for total phytoplankton counts.

Variable	Parameter Estimate	Standard Error	P-value
Intercept	-221.336	85.129	0.01
Principal Comp. 1	15.176	5.028	0.00
Principal Comp. 2	43.458	14.677	0.00
Temp 0-25m	8.612	3.612	0.02
PO ₄ 0-25m	-6.913	2.479	0.01
NO _x 0-25m	-1.552	0.478	0.00
SiO ₂ 0-25m	-0.387	0.124	0.00
Temp_lag1 0-25m	11.289	3.797	0.00
PO ₄ _lag 1 0-25m	-6.419	2.568	0.02
NO _x _lag1 0-25m	-0.818	0.265	0.00
SiO ₂ _lag1 0-25m	-0.354	0.126	0.01
SiO ₂ 100m	-0.059	0.030	0.06
PO ₄ _lag1 100m	0.855	0.397	0.04

Significant factors in the model were positive correlations with principal components one and two (the combination of both surface and bottom nutrients including time-lagged data) and with temperature in surface waters (both time-lagged and on the day of sampling) (Table 5). This indicated that the combination of both nutrient concentrations and water temperature up to a week prior to, and on the day of sampling, might be important factors in determining phytoplankton densities at the 100m station. Other significant effects on phytoplankton counts included the individual effect of each of the nutrients, oxidised nitrogen, phosphate and silicate, in the surface waters at the time of sampling. The time-lagged effect of each of these individual nutrients was also significant. Silicate in bottom waters and a time-lagged phosphate effect in bottom waters were also found to have a significant association with phytoplankton counts. The expected values versus the observed values for the phytoplankton counts based on this model are shown in Figure 9.

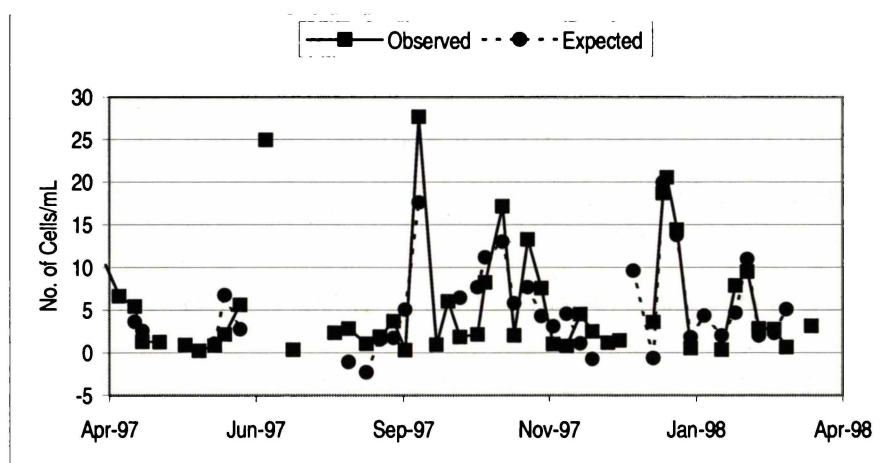


Figure 9. Observed and expected phytoplankton cell numbers at the Port Hacking 100m station (0-100m net haul).

Physicochemical variables not included in these analyses (due to either relatively poor data sets, ie. missing data, or having shown no direct correlation to phytoplankton counts eg ammonia) were then plotted against the residuals to investigate whether these variables exhibited any potential relationship that might not have been included in these models. No relationship between these variables and the residuals from the regression model were observed.

Discussion

Physicochemical Data

The long-term patterns in physicochemical characteristics of the water column off Sydney have been summarised by RENDELL and PRITCHARD (1996). Thermal stratification in spring, summer and early autumn is associated with low nutrient concentrations in surface waters, increasing with depth and coupled with seasonal nutrient cycles in both surface and deeper waters. We confirmed these patterns in the present study. Average surface (0-25 m) concentrations of oxidised nitrogen (12 µg/L) and phosphate (5µg/L), and bottom water concentrations of 125 µg/L (oxidised nitrogen) and 21 µg/L (phosphate) measured in this study, were consistently within the range of concentrations previously determined in these waters (NEWELL, 1966; HAHN *et al.*, 1977; ROCHFORD, 1984; TRANTER *et al.*, 1986; CRESSWELL, 1994; COADE, 1995). Maximum nutrient concentrations in bottom waters experienced during August to April were characteristic of cold nutrient-rich slope water that moved onto the shelf. These intruded waters typically have low temperature (<14°C) and salinity (<35.3‰), and high nutrient concentrations. They are thought to be the main source of nutrients into these waters and are therefore an important feature of Sydney's coastal environment (RENDELL and PRITCHARD, 1996).

Three deepwater ocean outfalls commissioned in the early 1990s along this coastline relocated significant quantities of extra nutrients into Sydney's offshore environment. Each day, these outfalls together contribute an average of 36,200 kg of total Kjeldahl nitrogen (24,800 kg as ammonia nitrogen) and 6,700 kg of phosphorus (total) to coastal waters (PRITCHARD *et al.*, 1996). Discharges from these sewage outfalls are continuous and since almost all the nitrogen is delivered in the form of ammonia, it is not surprising that concentrations measured directly downstream of the outfalls reached levels of up to 120 µg/L (median effluent concentrations were 22-29 mg/L; outfalls achieve two orders of magnitude initial dilution, EPA, 1996). Due to the dilution and/or

dispersion of this effluent or rapid utilisation by the phytoplankton, no significant increase in ammonia could be detected at the Port Hacking station. Ammonia concentrations measured during this study were generally consistent with background concentrations from the Sydney region (PRITCHARD *et al.*, 1998). Maximum concentrations of ammonia during this sampling period corresponded with the collapse of blooms of the red-tide species, *Noctiluca scintillans*. *N. scintillans* aggregations may release ammonia into the environment when the cells cease to feed and begin to lyse (OKAICHI and NISHIO, 1976; SCHAUMANN *et al.*, 1988).

Nutrient concentrations in these waters show considerable variability over time with long-term trends in CSIRO data suggesting possible increases in phosphate concentrations (Table 6). Nutrient ratios, that is, the ratio of dissolved inorganic nitrogen to dissolved reactive phosphorus (DIN:DIP), and dissolved reactive silicate to dissolved reactive phosphorus (DIS:DIP) calculated from this long-term data set, however, show no clear trend to date. Oceanographic variations such as El Niño and anthropogenic nutrient contributions to the coastal zone are all factors that may influence the nutrient distribution in these coastal waters (HALLEGRAEFF, 1933). LEE *et al.*, (2001) discusses the long-term variability of this data in terms of climatic variability.

Table 6. Results of a Correlation Analysis using the Pearson Correlation Coefficient (significant at $\alpha=0.05$) for nutrient concentrations over time at the long-term Port Hacking 100m station.

PHOSPHATE 1957-1985				NITRATE 1966-1995			
Depth	Correlation Coefficient	P-value	Significance	Depth	Correlation Coefficient	P-value	Significance
0m	0.01	0.95	NS	0m	0.15	0.44	NS
10m	-0.07	0.70	NS	10m	0.14	0.47	NS
			NS	25m	0.11	0.65	NS
50m	0.09	0.66	NS	50m	-0.11	0.58	NS
75m	0.29	0.24	NS	75m	0.02	0.93	NS
100m	0.71	0.001	*	100m	-0.18	0.34	NS

Focussing on the comparative work by HALLEGRAEFF and REID (1986) in 1978-79 and the present study, several differences become apparent. The 1997-98 year was generally warmer principally during winter and in the upper mixed layer in summer. Bottom waters during 1997-98 were 1-2°C warmer, with slope water moving onto the shelf but not uplifting into the surface waters as in 1978-79. Nutrient concentrations (oxidised nitrogen and phosphate), were less in bottom waters compared to 1978-79. Silicate concentrations however, were similar in the present study compared to 1978-79. The reason for these differences is unclear but this shift in nutrient availability may be important in the shift in phytoplankton dominance from the pennate genus *Pseudo-nitzschia* in previous years to the small centric diatom *Thalassiosira* in this study.

The Phytoplankton Community

The abundance data from this study shows short-lived (1-3 week) peaks in algal densities in conjunction with slope-water intrusions. This association is not as obvious when the annual pattern of chlorophyll *a* concentrations is examined. The difference between the annual chlorophyll *a* pattern and the annual pattern in phytoplankton abundance is due to the variation in chlorophyll *a* content of different phytoplankton taxa - certain phytoplankton contain higher concentrations of chlorophyll *a* in their cells than others (JEFFREY and HALLEGRAEFF, 1990). While chlorophyll *a* is an overall measure of phytoplankton biomass, each chlorophyll *a* peak may represent a unique phytoplankton assemblage. Chlorophyll *a* content of phytoplankton cells is also influenced by many environmental conditions including temperature, past light intensity and nutrient deficiency (EPPLEY, 1966). However, if differences in chlorophyll concentrations at a cellular level are not examined in detail, the annual chlorophyll *a* pattern from 1978-79 compared to that seen in the present study are in remarkable agreement (Figure10).

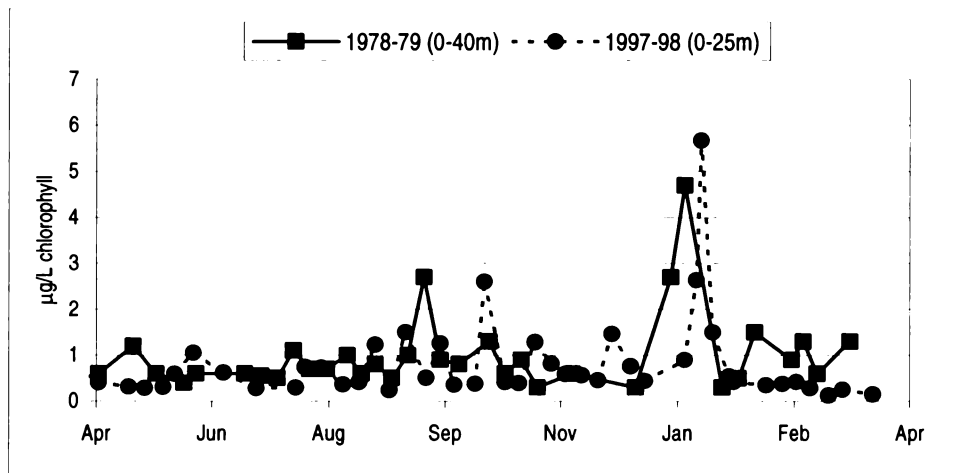


Figure 10. Annual chlorophyll a pattern at the Port Hacking 100m station.

In terms of chlorophyll a concentration and total cell densities, this suggests that there has been no discernible change in the overall biomass in these waters in the past ten years. Early phytoplankton studies off Sydney described the plankton community in terms of the dominant taxa only, with little attention paid to any diversity or abundance measure. *Asterionella japonica* (now *Asterionellopsis glacialis*), *Nitzschia seriata* (now *Pseudo-nitzschia fraudulenta*), *Chaetoceros* sp., *Rhizosolenia* sp., *Stephanophyxis* sp., *Leptocylindrus* sp., *Biddulphia* sp., *Skeletonema* sp., *Thalassiosira* sp. and the dinoflagellate, *Ceratium furca* were identified as the most commonly encountered taxa in the phytoplankton community (DAKIN & COLEFAX, 1933, 1940; SHEARD, 1949).

GRANT and KERR (1970) studied phytoplankton abundance and species and their relationship to the physical environment during the period April 1965 and April 1966. Counts of cells ranged from 2.25 to 10×10^4 cells per litre with dominant species being *Asterionellopsis glacialis*, *Leptocylindrus danicus*, *Navicula* sp., *Nitzschia seriata*, *N. longissima*, *Rhizosolenia alata*, and *R. stolterforthii*. In addition to these taxa, *Detonula* sp. and *Eucampia* sp. were also listed as common in these waters (HALLEGRAEFF, 1981).

There appear to be few differences in the overall species diversity, maximum cell counts, or the succession of spring and summer bloom

species encountered in our study compared to previous studies. One anomaly between the phytoplankton assemblages from the two years sampled is the presence of many tropical indicator species in 1997-98 compared to 1978-79. Examples of these are *Bacteriastrum* sp., *Ceratium gravidum*, *Ceratocorys horrida*, *Hemialus hauckii*, *Ornithocercus magnificus*, *Phalocroma argus* and *P. circumsutum*, *Pseudoeunotia doliolus*, *Scyphosphaera apsteinii* and *Trichodesmium erythraeum*. These species would have been transported into NSW waters by a strong southward flow of the East Australian Current. This is also seen in the climatically clear difference between the two sampling years, with the presence of a strong El Niño during 1997-98, whilst normal conditions were prevalent during the 1978-79 study.

Other differences are seen in the dominant species during the spring and summer blooms. *Asterionellopsis* sp. and *Pseudo-nitzschia fraudulenta* have been previously documented as the most common bloom species in these waters. In the present study, however, *Asterionellopsis* sp. was observed infrequently, and *Pseudo-nitzschia* sp. showed only a minor bloom in February 98. The small centric diatom, *Thalassiosira partheneia*, was recorded as the dominant bloom species throughout the present study. In addition, the frequency of occurrence throughout the year of *N. scintillans* at this location is unprecedented.

While it is known that microflagellates can outcompete dinoflagellates under eutrophic conditions, the competitive advantages of diatoms over other marine phytoplankton are unclear. RIEGMAN *et al.* (1996) investigated ecological niches, in terms of growth potential between different phytoplankton species (dinoflagellates, diatoms and prymnesiophytes), under different nutrient and light regimes. The dinoflagellates were poor competitors compared to the Prymnesiophyceae and, while some diatom species clearly had the ability to outcompete non-diatoms, other species of diatoms proved poor competitors. Other competition experiments by SOMMER (1994) showed that diatoms became dominant at Si:N (total) ratios > 25:1 while flagellates were the

superior competitors at lower ratios. *Thalassiosira* sp. was obviously favoured by the hydrological conditions at the Port Hacking station during this sampling year, that is, higher silicate and overall warmer waters than previous years.

The competitive advantages of the large colony-forming species, *Thalassiosira partheneia* over other phytoplankton in these waters are yet to be determined. The colonies are formed by the excretion of polymers by the individual cells. These polymers result in the colony being more viscous than the surrounding seawater, which may provide a hydrodynamic advantage in terms of sinking rates and surrounding shearfields (SMAYDA, 1997). Colony formation may also assist in survival due to a reduction in grazing pressure.

In a major upwelling region in north-west Africa, *T. partheneia* was abundant in surface waters down to 50m, but rarely below the euphotic zone (ELBRACHTER, 1982). SCHNACK (1983) demonstrated that although this species is an important food source for zooplankton in these areas of upwelling, copepods are only able to feed on these cells after disintegration from the healthy, whole colonies (possibly due to nutrient limitation, bacterial/virus action or damage due to UV radiation). In Sydney coastal waters, *N. scintillans* may also feed on these cells in this way.

The Noctiluca Phenomenon

Noctiluca scintillans (Macartney) has long been present in Australian waters with its earliest mention in NSW coastal waters by DAKIN and COLEFAX in 1933 as a relatively minor component of the phytoplankton community in Sydney coastal waters. HALLEGRAEFF (1995) collated a historic overview of visible algal blooms in NSW with the first visible bloom of *N. scintillans* recorded in August 1992. Since then, *N. scintillans* blooms appear to have increased in frequency and intensity, with the majority of blooms recorded in recent years (MURRAY and SUTHERS, 1999). The apparent increase in this species coincides with the global

concern of this species as a eutrophication indicator (PORUMB, 1992; QI *et al.*, 1993; LU *et al.*, 1994; HUANG and QI, 1997).

N. scintillans can indiscriminately devour a variety of prey items, including copepod eggs and phytoplankton, although not all food particles equally support growth and cell division (ELBRACHTER and QI, 1998). BUSKEY (1995) demonstrated that of nine phytoplankton species offered, a maximum growth rate was achieved with *Thalassiosira* sp. cell concentrations equivalent to $>0.5 \text{ mg C l}^{-1}$. Feeding experiments (with *N. scintillans* collected from local waters) will be required to provide information on their nutritional status and prey preference in these waters. It is hypothesised that the shift observed in 1997-98 in diatom dominance to *Thalassiosira* could be a major contributing factor to the increase in these red tide dinoflagellates.

Factors favouring algal blooms

The factors responsible for the distribution and seasonal successions of phytoplankton have previously been summarised as physical (temperature, light, water movements, density distribution), chemical (inorganic substances, organic substances) and biological (grazing, life histories etc) (JEFFREY and HALLEGRAEFF, 1990). An empirical model was devised in this study based on a selection of these variables (those which demonstrated significant correlations to total phytoplankton cell counts). It identified the most influential environmental factors on total phytoplankton biomass to be bottom water nutrients and temperature, as well as surface nutrients and temperature (including time-lagged data, which allowed for bloom 'incubation'). The forecasting ability of a multiple linear regression to explain the variation in total phytoplankton abundance was relatively high at $r^2=0.7$, with the combination of both surface and bottom nutrients as well as temperature (surface and bottom) being the most important environmental variables.

Temperature, both in surface waters and bottom waters was a significant factor in promoting the onset and the duration of the phytoplankton maximum. Phytoplankton abundance was high when water temperatures

were low (both surface and bottom water) and the water column became thermally stratified. This is also the time when the colder nutrient-rich water intrudes onto the shelf and when vertical mixing is at a peak. Low phosphate and low oxidised nitrogen concentrations in surface waters were also identified as being linked with high phytoplankton abundance (and associated low diversity). Rapid uptake (and therefore a depletion in surface waters) of these nutrients by phytoplankton is associated with increased biological activity. This suggests that while dissolved nutrients in the water may appear low, nutrient cycling may be considerable. In addition to this, the previous week's cool water temperature and elevated nutrient concentrations are significant factors that promote phytoplankton growth. This 'time lag' effect is important for bloom incubation.

All phytoplankton blooms investigated throughout our three-year ocean nutrient study (in the coastal waters between Port Stephens and Jervis Bay and encompassing the coastal waters off Newcastle, Sydney and Wollongong) have coincided with these slope water intrusions. These intrusions can occur with apparent continuity over length scales of hundreds of kilometres and do not appear to be influenced by proximity to major outfalls (PRITCHARD *et al.*, 1999).

Species-specific requirements for temperature and nutrients are also important in determining the dominance of particular species or algal group. Spring diatom bloom species flourish within the spring temperature ranges, while *N. scintillans* requires the optimum summer temperature of 19-24°C (LEE and HIRAYAMA, 1992; WU *et al.*, 1994; UHLIG and SAHLING, 1995). *Trichodesmium erythraeum*, a tropical/subtropical species capable of fixing atmospheric nitrogen, reaches maximal abundance in these waters when water temperatures are high and nutrient concentrations are impoverished (HALLEGRAEFF, 1933). At the Port Hacking location *T. erythraeum* was most abundant in April when surface waters were >~22°C. The introduction of warmer surface layer temperatures followed by the increase in water column stratification may

be an important trigger for the succession of one phytoplankton group to another.

Conclusions

Phytoplankton blooms appeared to occur in response to slope water intrusions (upwelling/uplifting) lasting 2-22 days and occurring from September to February. Bottom-and surface water nutrients and temperature explained 60% of the variability of phytoplankton biomass throughout the year. Phytoplankton blooms of similar frequency and magnitude to those seen in this study have been previously recorded. In contrast to earlier work, however, where a variety of taxa dominated throughout the year, the small diatom *Thalassiosira partheneia* generally dominated blooms in this study. In addition the heterotrophic dinoflagellate, *Noctiluca scintillans*, was present more frequently (61% of samples collected throughout the year). The reason for the recent dominance of these particular phytoplankters is unclear but may be related to physico-chemical conditions such as a decrease in phosphate and oxidised nitrogen concentrations and warmer water temperatures experienced during our sampling period compared to previous years.

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Appendix 1. Phytoplankton Taxa List from the Port Hacking 100m Station.

1	Amphisolenia bidentata	56	<i>Hemiaulus</i> sp.*
2	<i>Amphisolenia</i> sp.	57	<i>Lauderia annulata</i>
3	<i>Amylax triacantha</i> *	58	<i>Leptocylindrus</i> spp.
4	<i>Asterionellopsis glacialis</i>	59	<i>Lioloma</i> spp.
5	<i>Asteromphalus heptactis</i>	60	<i>Melosira</i> sp.
6	<i>Asteromphalus</i> sp.	61	<i>Meringosphaera</i> sp.
7	<i>Bacteriastrum</i> sp.	62	<i>Meuniera membranacea</i>
8	<i>Biddulphia/Odontella</i> sp.	63	<i>Minidiscus trioculatus</i>
9	<i>Cerataulina pelagica</i>	64	<i>Navicula</i> spp.
10	<i>Ceratium candelabrum</i>	65	<i>Nitzschia (Cylindrotheca)</i> <i>closterium/longissima</i>
11	<i>Ceratium carriense</i>	66	<i>Noctiluca scintillans</i>
12	<i>Ceratium falcatum</i>	67	<i>Ornithocercus magnificus</i>
13	<i>Ceratium furca</i>	68	<i>Ornithocercus</i> spp.
14	<i>Ceratium fusus</i>	69	<i>Oxytoxum</i> spp.
15	<i>Ceratium gravidum</i> *	70	<i>Phalacroma argus</i> *
16	<i>Ceratium horridum</i>	71	<i>Phalacroma circumsutum</i> *
17	<i>Ceratium lineatum</i>	72	<i>Phalacroma</i> spp.
18	<i>Ceratium lunula</i>	73	<i>Phalchroma rotundatum</i>
19	<i>Ceratium macroceros</i> *	74	<i>Planktoniella sol</i>
20	<i>Ceratium pentagonum</i>	75	<i>Pleurosigma</i> spp.
21	<i>Ceratium</i> sp.	76	<i>Pleurosigma chilensis</i> *
22	<i>Ceratium trichoceros</i>	77	<i>Podolampus bipes</i>
23	<i>Ceratium tripos</i>	78	<i>Podolampus</i> sp.
24	<i>Ceratocorys horrida</i> *	79	<i>Prorocentrum triestinum</i>
25		80	<i>Prorocentrum lima</i>
	Chaetoceros spp.		
26	<i>Climacodium frauenfeldianum</i>	81	<i>Prorocentrum minimum</i>
27	<i>Cocconeis</i> sp.	82	<i>Prorocentrum</i> spp.
28	<i>Corethron</i> sp.	83	<i>Protoperidinium bipes</i>
29	<i>Corythodinium elegans/tesselatum</i>	84	<i>Protoperidinium divergens</i>
30	<i>Coscinodiscus</i> spp.	85	<i>Protoperidinium pellucidum</i>
31	<i>Detonula pumila</i>	86	<i>Protoperidinium pentagonum</i>
32	<i>Dictyocha fibula</i> *	87	<i>Protoperidinium</i> spp.
33	<i>Dictyocha octonaria</i> *	88	<i>Pseudoeunotia doliolus</i>
34	<i>Dictyocha speculum</i> *	89	<i>Pseudo-nitzschia australis</i> *
35	<i>Dinophysis acuminata</i> *	90	<i>Pseudo-nitzschia heimii</i> *
36	<i>Dinophysis acuta</i> *	91	<i>Pseudo-nitzschia</i> <i>pseudodelicatissima</i> *
37	<i>Dinophysis caudata</i>	92	<i>Pseudo-nitzschia multiseries</i> *
38	<i>Dinophysis fortii</i>	93	
			Pseudo-nitzschia pungens
39	<i>Dinophysis schuetti</i>	94	<i>Pseudo-nitzschia</i> cf. <i>subfraudulenta</i> *
40	<i>Dinophysis tripos</i>	95	<i>Pseudo-nitzschia subpacifica</i> *
41	<i>Diploneis</i> sp.	96	<i>Ptychodiscus noctiluca</i> *

42	<i>Diplopsalis</i> sp.	97	<i>Pyrocystis</i> sp.
43	<i>Ditylum brightwellii</i>	98	<i>Rhizosolenia</i> spp./ <i>Proboscia</i> spp.
44	<i>Emiliana huxleyi</i> / <i>Gephyrocapsa oceanica</i>	99	<i>Scrippsiella trochoidea</i>
45	<i>Eucampia cornuta</i>	100	<i>Scyphosphaera apsteinii</i> *
46	<i>Eucampia zodiacus</i>	101	<i>Skeletonema costatum</i>
47	<i>Goniodoma</i> sp.	102	<i>Stephanopyxis turris</i>
48	<i>Gonyaulax</i> spp.	103	<i>Thalassionema nitzschioides</i>
49	<i>Guinardia delicatula</i>	104	<i>Thalassionema</i> spp.
50	<i>Guinardia flaccida</i>	105	<i>Thalassiosira</i> spp.
51	<i>Guinardia striata</i>	106	
			Thalassiosira partheneia
52	<i>Gymnodinium</i> (/Gyrodinium) spp.	107	<i>Trichodesmium erythraeum</i>
53	<i>Helicotheca tamesis</i>	108	Unidentified diatoms
54	<i>Hemiaulus hauckii</i> *	109	Unidentified flagellates
55	Hemiaulus membranaceus *	110	Unidentified nanoplankton

* not listed by Hallegraeff and Reid 1986

6-4 CHAPTER CONCLUSIONS

In addressing the first two thesis objectives, the chapter findings have detailed how the oceanic nutrient sources limit phytoplankton abundance in the coastal waters, in accordance with their seasonal enrichment and circulation patterns. From the investigations undertaken during the program and with reference to historical records, there were no clear responses to rainfall events or any "downstream" effect from the Sydney outfalls. The anomalous bloom event in January 1998 provided an example of how phytoplankton succession occurs according to the environmental preferences of individual species involved. With the source of this anomaly considered to be the result of inter-annual climate fluctuations, the following chapter places the event into greater context by examining long-term records to define the strength of this anomaly with respect to seasonal patterns. Although the studies here clearly indicate that phytoplankton are responding to these intrusion events, the succeeding discussion chapter re-introduces anthropogenic sources for a comparative assessment with oceanically derived concentrations and loads. It also explores whether the characteristics of these anthropogenic discharges are likely to influence these seasonal phytoplankton populations.

Chapter 7: Long-term Patterns

7-1 CONTEXT OF PAPER WITHIN THE THESIS

Short-term investigations are frequently undertaken in coastal areas to assess the effect of an introduced impact (pollutant, hydrodynamic structure etc). Such studies often attempt to extrapolate the results beyond their limits, however to successfully achieve this it is necessary to understand their context with respect to spatial and temporal scaling. Spatially the study needs to consider parameters such as regional coastal current patterns, coastal topography, proximity to estuaries and anthropogenic inputs, to indicate the area over which study results bear relevance. Temporally, the study needs to consider scales ranging from hourly to climatic. Most studies consider scales accounting for tidal, diurnal, weather-band and seasonal oscillations, but do not account for inter-annual fluctuations or long term trends. It may be considered reasonable to assume that long-term patterns in the ocean would affect the background variability at a study's impact and control sites equally. However, if a long-term pattern changed the nature of the impact by either affecting its distribution or the environmental sensitivity, then studies of this type, could have identified impacts (or lack of impacts) which are unrepresentative. This prompts the question;

Was the ONPP conducted during a period when unusual conditions favoured specific phytoplankton populations and, if so, would more 'typical' conditions put a greater, or a lesser, stress on the environment?

Although intra-seasonal patterns dominate ambient conditions in the coastal waters of the study region, long-term climatic signals, such as the El Niño Southern Oscillation (ENSO), have been influential during earlier studies undertaken by the NSW EPA (Lee and Pritchard, 1996).

The following paper explores these questions and uncertainties. This paper was published in the Journal of Coastal research in 2001, as the following reference.

Lee, R.S., Ajani, P.A., Pritchard, T. R., and Black, K.P., (2000). Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia. Journal of Coastal Research, 34, p. 74-86.

7-2 RESOLVING CLIMATIC VARIANCE IN THE CONTEXT OF RETROSPECTIVE PHYTOPLANKTON PATTERN INVESTIGATIONS OFF THE EAST COAST OF AUSTRALIA

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Running Head: Climate variation at a coastal monitoring station off
Australia's east coast.

Abstract

Many oceanographic studies on the eastern seaboard of Australia have utilised as a benchmark, the long-term records from the Commonwealth Scientific and Industrial Research Organisation 50 and 100m sites off Port Hacking, near Sydney. This 57-year physico-chemical record is tested for bias (eg. 'fair weather' sampling bias), to assess the degree to which temporal variability is captured and to assess potential for spatial extrapolation. The data is found to be well correlated for all-weather conditions, and indicates there is an alongshore, cooling trend in the region that may be related to shelf break divergence. We explore this record for long-term patterns and their association with the known large-scale phenomenon, El Niño. Discrete short-term biological (phytoplankton) and physico-chemical studies, interpreted in the context of long-term background climatic variability indicate anomalous conditions that appear to be related to El Niño. Warmer conditions associated with reduced nutrient levels were experienced during a recent study undertaken by Ajani et al (this volume) during the strong El Niño of 1997/98. These anomalies are similar to measured differences between normal and El Niño years experienced at the study site over the 57-year record. A comparison of this anomalous year to previous phytoplankton studies done at the Port Hacking 100m station suggests the anomalous physico-chemical conditions corresponded with atypical phytoplankton blooms of *Thalassiasira spp.* and *Noctiluca scintillans*. These results indicate that a better understanding of climatic variance is required when attempting to define impacts (such as anthropogenic inputs) on a coastal system from short-term studies. This approach enables a more thorough interpretation of current and historical data sets especially in cases where appropriate reference/control (putatively unimpacted) sites were unavailable or not monitored.

Index words: upwelling, nutrients, El Niño, phytoplankton

Introduction

The progressive growth in reliable long-term data records provides the basis to assess climatic variance beyond relatively predictable seasonal patterns. As a result, longer-term fluctuations such as the El Niño Southern Oscillation (ENSO) and La Niña (anti-ENSO) events are now widely accepted within and beyond the scientific community. With international programs to monitor and predict ENSO now operational in the Pacific, the many local manifestations of ENSO are garnering much interest. A number of studies have linked ENSO signals in coastal waters to fluctuations in local productivity. A well known link is described by Arntz (1984) for coastal waters off Peru where 2-5°C increases in the sea surface temperature (SST), signals the shutdown of large scale upwellings and a demise of the local anchovy harvest. Similar effects are seen in coastal waters off SW Taiwan where Tsai *et al* (1997) noted lagged SST anomalies coincided with ENSO cycles and the abundance of larval anchovy.

Markedly reduced phytoplankton blooms in the NW Arabian Sea were considered by Brock and McClain (1992) to be the result of diminished coastal upwellings associated with a weak SW monsoon that preceded the 1982/83 El Niño.

Within the Australian oceanographic region, ENSO causes fluctuations in the major coastal current systems causing a variety of changes in the biota. Off Perth in Western Australia, ENSO positively correlates with inter-annual sea level, temperature and salinity variations which relates inversely to the strength of the southward flowing Leeuwin Current (Caputi *et al*, 1996). The warm low salinity waters of the Leeuwin promote recruitment of tropical fish larvae and western rock lobster in the more southern coastal waters of Western Australia (Pearce and Phillips, 1988). Love (1987) correlates the SOI with the Banana Prawn catch in the Gulf of Carpentaria. As the prawns mature in rivers they become less tolerant to low salinity and move into the coastal ocean. Therefore the heavy rains

associated with a positive SOI (anti-ENSO) tend to promote greater prawn harvests by trawlers.

Fluctuations in the geostrophic western boundary current off Australia's east-coast, the East Australian Current (EAC), linked with inter-annual variations in the phytoplankton activity off the east coast of Tasmania had a profound effect on the recruitment to commercial stocks in Tasmanian waters (Harris *et al*, 1987). During ENSO years they found cooler summer maximum and warmer winter minimum temperatures associated with a reduced influence of the EAC.

Lee and Pritchard (1997) indicated that ENSO was affecting the southerly extent of the EAC, expressed as a reduction in temperature stratification on Australia's south-eastern seaboard off Sydney. This reduced density difference permitted Sydney's deepwater sewage discharges to surface more frequently and become prone to more agile wind induced transports, thereby increasing the potential for effluent movement towards Sydney's beaches.

A recent comparative study undertaken by Ajani *et al* (this volume) during the 1997/98 ENSO investigated phytoplankton abundance off Sydney. The work revisited 12 month sampling undertaken in 1978/79 by Hallegraeff (1981), to assess whether an increased anthropogenic influence (predominantly from the introduction of deepwater sewage discharge in 1990) had been associated with major changes to the phytoplankton population.

This paper addresses sampling bias in long-term data records to resolve their spatial and temporal limitations before applying them to assessing climatic fluctuations. We establish physico-chemical fluctuations associated with the ENSO signal, and determine whether they could affect

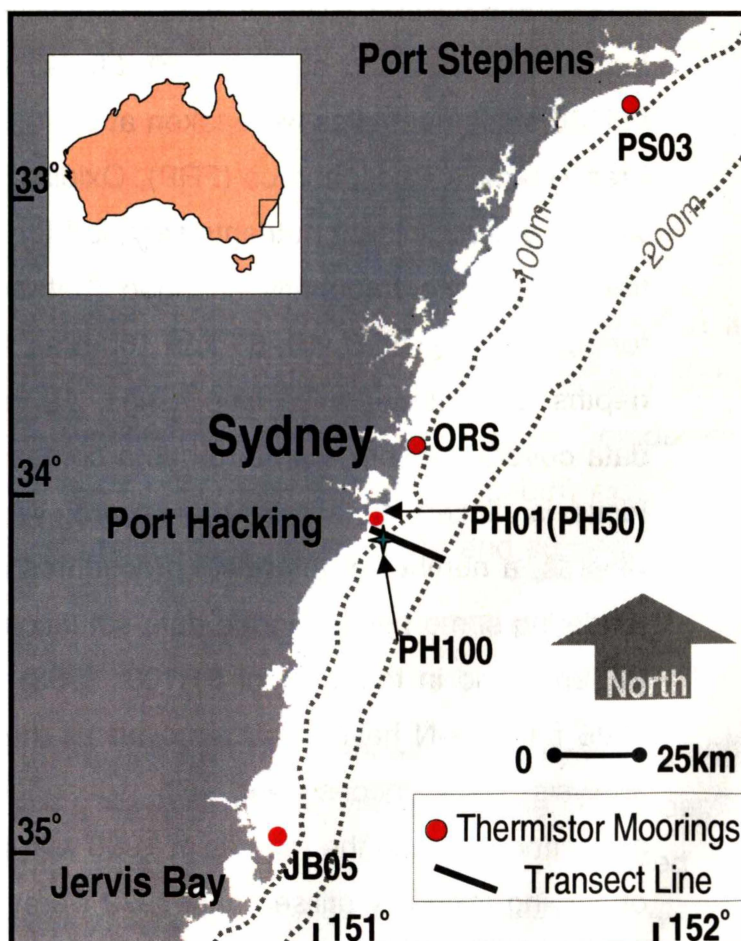
the interpretations of shorter, project-based investigations such as the comparative study by Ajani et al (2001).

Data and Methods

Overview

Concerns about coastal discharge of anthropogenic nutrients and an apparent increase of marine phytoplankton blooms (Smayda and White, 1990; Hallegraeff, 1995; Pan and Subba Rao, 1997) prompted a three-year, multi-disciplinary study by the NSW Environment Protection Authority (NSW EPA). This study focussed on a 300km stretch of the eastern seaboard of Australia where sewage (ocean outfalls), estuarine (during flooding) and oceanic (slope-water) nutrient sources dominate, and assessed the phytoplankton response. The NSW EPA study involved field investigations, reviews and the re-analysis of existing data sets to look at present comparative conditions, and retrospectively with previous investigations. The resultant combination of time series moorings, coastal sampling stations and shore normal transects used in this investigation are depicted in Figure 1.

Figure 1: Locality map showing sampling stations, transects and instrument moorings used in the investigation along a 300km stretch of the Australian eastern seaboard.



Long-term records

Continuous (hourly) temperature, current and wind records have been obtained from an instrumented buoy (the Ocean Reference Station, ORS) operated by Sydney Water Corporation. After initial trials in 1989, the ORS has been operating relatively continuously (apart from maintenance) ~4km offshore of Bondi, Sydney in 65m of water since November 1990. The buoy was configured with two S4P current meters located at 17m and 52m depth, 16 thermistors on a chain spanning the upper 52m of the profile, and two anemometers measuring near-surface wind.

Weekly to monthly sampling runs at Port Hacking, Sydney, have been in operation since 1942 by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) collecting temperature, salinity and nutrients through the water column at two stations, PH50 and PH100, located in 63m and 105m of water respectively (see Figure 1). The PH50 station was sampled at 0, 10, 20, 30, 40 and 50m depths, and at the PH100 station samples were taken at 0, 10, 25, 50, 75 and 100m depths. Free Reactive Phosphorous (FRP), Oxidised Nitrogen (NO_x-N) and silica were the predominant nutrients sampled for analysis. Sampling depths at the PH100 site frequently changed (between some 16 different depth formats), rendering 0, 10, 50 and 100m as the only consistently sampled depths for a comparative time series. As the PH50 station has a better data coverage over depth and has a comparable depth to the ORS, less focus is placed on the PH100 record. Within the timeframe of these records, a number of analytical procedures changed for nutrient analysis rendering some periods in the data-set incompatible. Sample results prior to 1957 (and in the case of PH100, 1953) for FRP, and values prior to 1965 for NO_x-N have been removed as the respective FRP and NO_x-N analysis were inconsistent with subsequent results. Silica analysis commenced late in the records in 1968 with a number of manual methods of varying accuracy utilised until 1972 (Airey and Storey, 1987). Between 1971 and 1984 a more accurate manual technique was adopted, and in

1984 all analysis became automated. The variable results prior to 1971, however, have been removed from our analysis.

Airey and Sandars (1987) provided comparisons of automated nutrient analysis to the previously employed manual techniques by CSIRO laboratories, and found that only for FRP were the two methods equivalent within the precision of the procedures for sampling, storage and analysis. Airey and Storey (1987) indicate that a ~10% adjustment would be required to compensate overestimated NO_x-N results from the analytical technique employed between 1975 and June 1984. For silica, a positive offset became apparent in the records when automated methods were introduced. Airey and Storey (1987) indicate that automated and manual comparisons from like regions, sampling depths and seasons, would provide an indication of the offset. Using this approach the offset for the Port Hacking data averaged ~30ug/L. The 10% adjustment for NO_x-N, and the 30ug/L silica offset, has been applied for our analysis of the PH50 & PH100 data.

Focussed Studies

Our 12-month weekly sampling program commenced in April 1997 in a manner consistent with monitoring undertaken by Hallegraeff (1981). Both studies focussed on quantitative phytoplankton and companion hydrographic sampling at the CSIRO Port Hacking long-term monitoring station (PH100), looking at abundances, distributions and successions of phytoplankton taxa.

A quantitative 20µm sampling net, identical to the unit used by Hallegraeff (1981), was used to collect a cumulative sample between the 0-50m depth representing the euphotic zone. The work was also accompanied by sampling for larger dinoflagellates and zooplankton using nets with a larger 100µm mesh size. Supporting the biological information was physio-chemical data collected by Seabird SBE25 CTD and 5-litre Niskin water

sampling (at depths similar to CSIRO station sampling) at both PH100 and PH50 sites at depths (see Figure 1). CTD profiling was extended both inshore and offshore of the PH50 & PH100 sites to form a 10km transect across the inner and mid-shelf zones. This allowed shelf dynamics to be examined in conjunction with the biological activity. Water sampling included ammonia, chlorophyll-a and algal count analysis to the standard suite of nutrients routinely sampled at PH50 and PH100 by the CSIRO.

A companion project to this study deployed twenty thermistor moorings in coastal waters (50-100m depths) along 300km of the coast centred about Sydney to regionally assess the frequency of cool slope-water intrusions (Lee et al, 2002). The four continuous moorings utilised in this paper (see Figure 1), were at the PH50 site (PH01), Port Stephens (PS02, PS03) some 150km to the north, and Jervis Bay (JB01) ~150km to the south. On each mooring Onset Tidbit temperature loggers ($\pm 0.1^{\circ}\text{C}$) collected hourly data at 2, 10 and 20m from the sea floor to focus on intruding slope-waters.

CTD and nutrient data were collected along shore-normal transects during the 1995/96 and 1996/97 summer upwelling seasons (see Figure 1). Transects consisting of nine stations out to the shelf break (200m contour) were taken off Port Stephens (45km), at Port Hacking (25m) and Jervis Bay (20km). At each station, continuous CTD profiles were taken and samples for $\text{NO}_x\text{-N}$, FRP, silica, ammonia, chlorophyll-a and algal counts were collected (depth depending) at 0, 10, 20, 50, 100, 150, 200 and 5m from the bottom. For all laboratory analysis appropriate blanks and duplicates were randomly included in the sampling, and inter-laboratory analysis were routinely carried out to ensure data quality.

Long-term Data Consistency

An initial comparison between ORS (52m) and PH50 (50m) is shown in Figure 2(a) where the long-term distributions for temperature are well

correlated but have an offset of $\sim 0.5^{\circ}\text{C}$, favouring warmer water at the ORS. This offset suggests either (long-term average) spatial variability is significant over relatively short alongshore distances (10's of km), or differences in sampling intervals may have biased results.

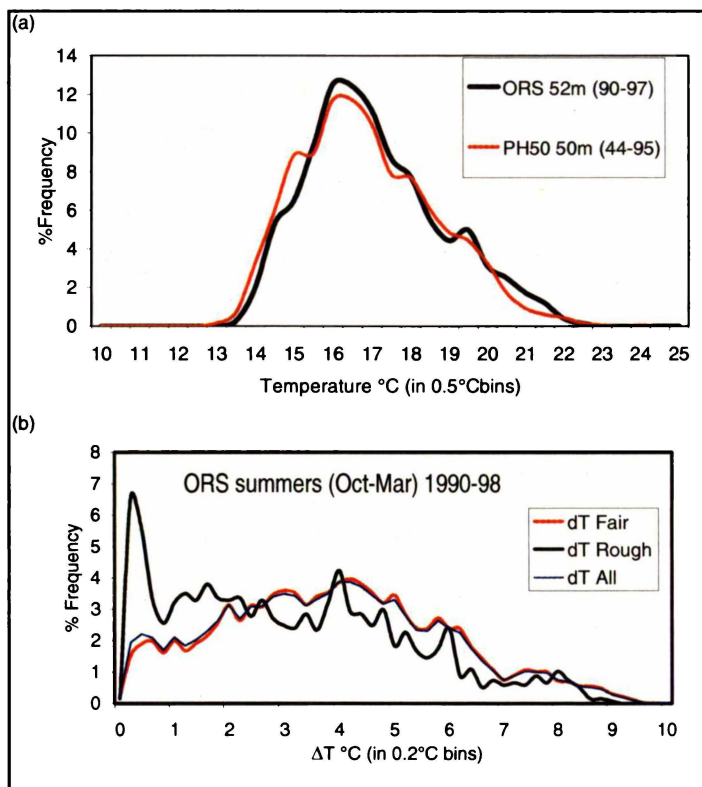
The ORS and PH50/PH100 sampling operated over different temporal scales. Clearly the 57 year Port Hacking record is well suited for assessing changes in climatology and any historical trends. However due to its sparseness in sampling, temporal scales less than an annual cycle are unable to be confidently resolved. The Port Hacking records may also show a bias towards calm weather conditions as measurements were predominantly taken from small vessels. Conversely, the near-continuous record from the ORS mooring captures all conditions within and across annual cycles. So before establishing the Port Hacking data set as a long-term reference, we examined ORS data to test for this “weather bias”.

The entire ORS temperature record (1990-98) was partitioned into representative bad and fair weather bins based upon concurrent wind strength measurements at the ORS. Bad weather was arbitrarily selected as conditions unlikely for small boats to venture out to sea. From experience, this is usually the case for winds of a prevailing strength of greater than 20 knots or $\sim 10\text{m/s}$. The ORS records were duly sub-sampled for wind events of $>10\text{m/s}$ whose duration was for 6 hours or more.

Frequency distributions of near-bottom temperature (52m) indicated a positive bias for bad weather conditions, with the frequency curve shifted $\sim 1^{\circ}\text{C}$. However, the criteria for rough weather only fitted $\sim 10\%$ of all the data, so when comparing the fair weather distribution to the all-weather plot, the differences are small ($<0.1^{\circ}\text{C}$). A stronger effect does appear on overall temperature stratification (ΔT) in Figure 2(b), with the major frequency peak for bad weather occurring in unstratified ($<1^{\circ}\text{C}$) conditions, while fair conditions were more evenly distributed about a ΔT peak of 4°C .

However, the fair weather distribution (simulating PH50 & 100 data record) is only marginally reduced for the unstratified condition when compared to an all weather record.

Figure 2: (a) The long-term distributions for bottom-water temperature at the Ocean Reference Station (52m) and the PH50 (50m). (b) Frequency distributions of temperature stratification (ΔT) from the Ocean Reference Station for fair, poor and all weather conditions (based on a 10m/s wind threshold), indicate the bias of poor weather is negligible with respect to all weather conditions.



As the ORS is 25km along the shelf to the north of PH50, roughly the same as the width of the shelf at this location, spatial differences should also be assessed. Average flow conditions at the ORS indicate a predominant southward alongshore component with cross-shelf current strengths $\sim 10\%$ of the alongshore stream. EAC influences from the north and a narrow shelf (20-25km orientated at $\sim 30^\circ$) promote this uniform alongshore stream with typical excursion times of ~ 30 hours between sites for ORS depth averaged flows (0.23m/s).

Looking regionally however, the shelf widens to the north (by 6km) and south (by 7km) of the PH50 site as the shoreline orientation (mimicked at the 50m contour) changes by $\sim 20^\circ$ in the vicinity of PH50, whilst the shelf-break maintains a 30° alignment. The narrowing may accelerate shelf flows (and increase bottom stress) in the vicinity of PH50, providing a mechanism for uplifting cooler waters (as indicated by Oke and Middleton,

1999). The inflection in the coastal contours could cause an offshore divergence of the EAC, which could result in some recirculation experienced at the PH50 site. In this shelf environment, the Rossby radius is calculated at ~10km, which is consistent with the scales of small cold-core back-eddy (clock-wise) observed from SST imagery on the shelf inshore of a shelf-break focussed EAC flow (Oke and Middleton, 2001). Although such features are not always apparent in SST imagery, they may explain the offset observed in Figure 2(a).

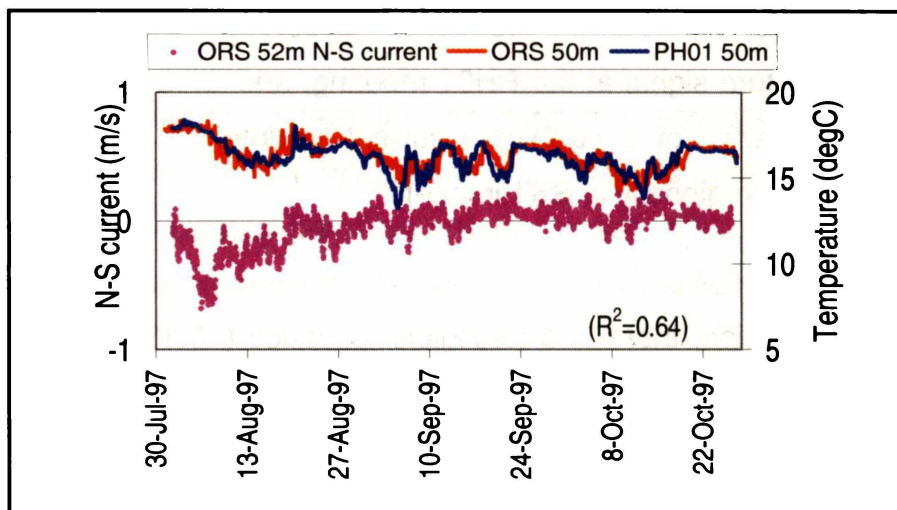


Figure 3: Coincident ORS (52m) and PH01 (50m) temperature time series data July-November 1997 and the alongshore ORS (52m) current.

Considering these physical attributes, it appears that the PH50 site could experience cooler water than the measurements at the ORS suggest. It is therefore instructive to compare continuous measurements made simultaneously at both sites. A four-month, bottom-water temperature record from the PH01 mooring in Figure 3 provides such an opportunity. The 50m thermistor was selected from the PH01 mooring (in 63m depth), as a best match to the ORS temperature at 52m in 65m depth. Data was low pass filtered at 25 hours to remove high frequency signals (tides, diurnal oscillations, internal waves) prior to their comparison in Figure 3.

Subsequent regression analysis confirms that the two data sets are significantly correlated ($R^2=0.64$), with similar patterns experienced at both sites on scales ranging from days to months. Also of note are the lags of approximately +/- 20-30hrs, that correspond to the sign of the alongshore, current component (provided in Figure 3), and the travel time for the 25km distance by an average current. The cooler temperatures (of up to 1°C less) experienced at the PH01 site compared to the ORS during intrusion events in September 1997, result in a mean temperature for the four month period to be 0.25°C cooler at the PH01 50m location. During the intrusions the thermal response observed at the ORS lags the temperature signal at the PH01 mooring, and ORS 52m currents suggest the presence of a northward current, counter to southward EAC flows occurring regionally in SST imagery.

In conclusion, there is a negligible influence (<0.1°C) of weather biasing on the bottom temperature record. The majority of the offset between the long-term PH50 and ORS records in Figure 2., appears to be due to alongshore small-scale spatial variability.

Having established that the PH50 and PH100 records appear to represent ~all-weather conditions (that may be coherent for a region +/- 10kms alongshore as defined by the local Rossby radius), in the next sections we assess the well-established temperature and nutrient slope-water criteria for defining water bodies. The remainder of the paper examines the slope-water signals on the shelf in relation to both seasonal and long-term climatic variances.

Results and Discussion

Slope-water Intrusions to coastal waters

From studies by Rochford (1984), MacClean-Padman and Padman (1991) and Cresswell (1994), nutrient rich water originating from the continental slope is uplifted onto the NSW shelf and brought inshore by the EAC

dynamics and/or upwelling favourable winds from the NE. A variety of mechanisms observed along the NSW shelf induce onshore transport of slope-water by the EAC (Oke and Middleton, 2001). Changes in bottom stress from a persistent alongshore EAC flow due to changes in shelf dimension, draws slope-water onto the shelf. Similarly divergent surface flow from an EAC eddy encroachment can entrain slope-waters onto the shelf to maintain geostrophic balance. Ekman pumping of cold core eddies formed in the lee of major coastal topographic protrusions can uplift shelf bottom-waters to the euphotic zone (Oke and Middleton, 2001).

The slope-water signal is seen inshore during the spring/summer season when thermal stratification develops and the EAC is more dynamic. This coincides with enhanced plankton activity (Newell, 1966; Hallegraeff and Jeffrey, 1993), and imposes a seasonal trend on local fisheries.

Defining the presence of Slope-water

Slope-water has been parameterised by Humphrey (1960), Newell (1966) and Cresswell (1994) as having properties of (1) temperature $\leq 14^{\circ}\text{C}$, (2) oxidised nitrogen 70-140 $\mu\text{g/L}$, and (3) FRP 20-25 $\mu\text{g/L}$. It is desirable to see how well the data records fit these ranges, and to perhaps refine them. Table 1 compiles information in the bottom-water layer (below the thermocline) for both PH50 (>30m depth) and PH100 (>50m depth) sites where slope-waters are likely to intrude.

Table 1. Medians and ranges of Physico-chemical data from water below the thermocline at long-term Port Hacking 50m and 100m sites.

Measured Value	Slope-water Criteria	PH50 30-50m			PH100 50-100m		
		Median	Min	Max	Median	Min	Max
Temperature $^{\circ}\text{C}$	≤ 14	17.01	12.7	24	15.92	11.6	25
NOx-N $\mu\text{g/L}$	70-140	46.6	.4	232	93.24	.5	258
FRP $\mu\text{g/L}$	20-25	12.7	.4	44	17.34	.6	56
Salinity psu	NA	35.46	34.5	35.95	35.43	33.75	35.95
Silica $\mu\text{g/L}$	NA	168	12	1322	216	30	901

Median ambient conditions for bottom-waters in Table 1, are well outside the slope-water criteria. The long-term bottom-water temperature and nutrient data satisfy the more stringent slope-water criteria for <10% of the time (~9% for PH100 and 2% for PH50). Inspecting these slope-water records over an average annual cycle, the contoured frequencies of temperature records $\leq 14^{\circ}\text{C}$ in Figure 4(a,b) show that intrusions are seasonally confined occurring between July and March. Within this period, intrusions are generally within 10m of the bottom at the PH50 site, and reach a maximum frequency of 6-10% in September-October. The PH100 site has a substantially higher frequency, with slope-waters confined to the lower 40m of the water column, reaching levels of 20-45% in September.

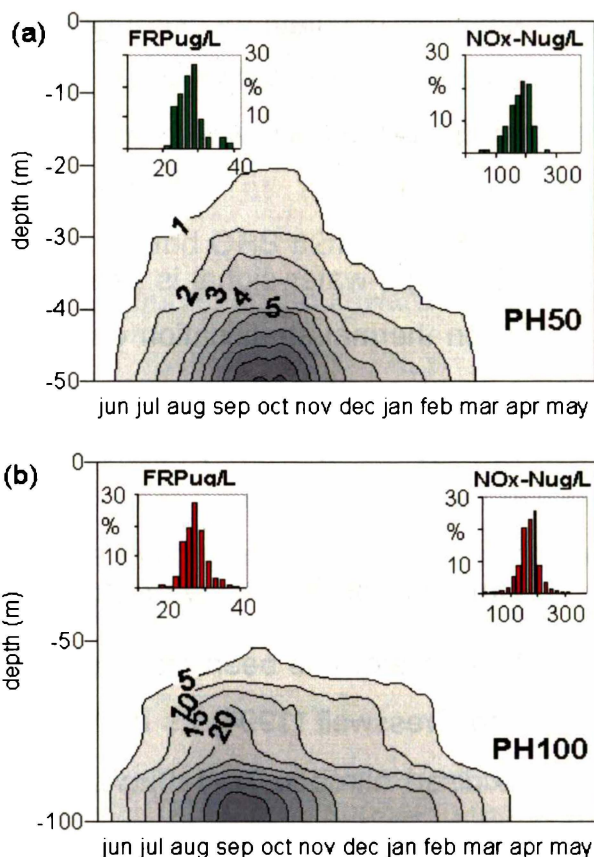


Figure 4: The contoured frequencies of temperature records $\leq 14^{\circ}\text{C}$ over an annual cycle, and nutrient distributions for slope-waters ($\leq 14^{\circ}\text{C}$) at the (a) PH50 and (b) PH100 sites.

The nutrient distributions given in Figure 4(a,b), are derived from the bottom-water records that satisfy slope-water temperatures ($\leq 14^{\circ}\text{C}$) during the upwelling season (July to March) at the PH50 and PH100 sites. The distributions are similar for both PH50 and PH100 suggesting that upwelling events that intrude to PH100 continue to PH50 in a relatively undiluted state. These values are marginally higher than the slope-water parameters prescribed by Humphrey (1960), possibly because our data set had partitioned bottom-waters during upwelling seasons. Referring to the nutrient distributions in Figure 4, and applying the prescribed slope-

water criteria, NO_x-N levels <100 µg/L occur for 8% of ≤14°C data, and FRP levels <20 µg/L for only 1% of ≤14°C data. This indicates that slope-water nutrient concentrations for the prescribed upwelling temperature criteria are clearly satisfied and are well above the average levels defined in Table 1.

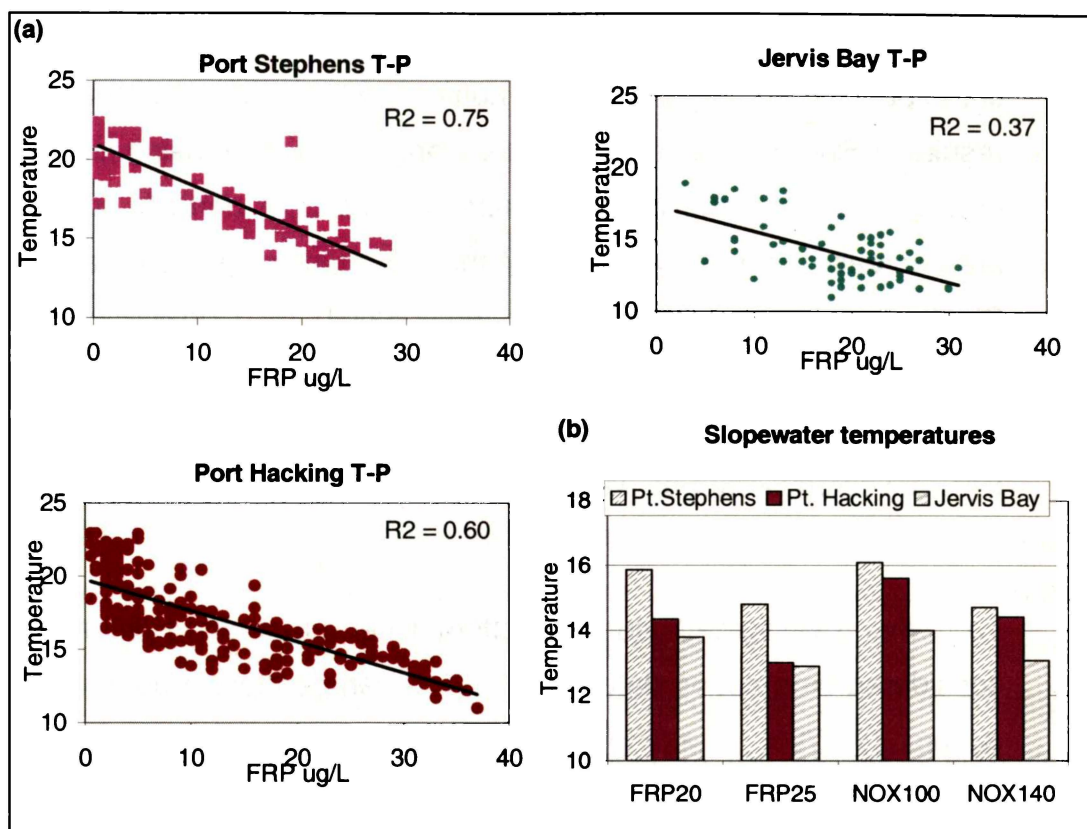


Figure 5:(a) The temperature-nutrient relationships for depths below the thermocline along 300kms of the continental shelf from Jervis Bay to Port Stephens. (b) indicative temperatures for threshold slope-water nutrients at the three transects.

To test these temperature and nutrient criteria alongshore from the Sydney region, transect data from Jervis Bay, Port Hacking and Port Stephens are compared. Figure 5(a) shows the temperature-FRP relationships for the three locations at depths below the thermocline. Similar relations were also seen for temperature-NO_x-N. Although sampling was not concurrent, the results are taken during the same upwelling periods over the two sampling seasons and so all represent general conditions of this period. Intuitively one expects that the cooler

bottom-waters experienced at the southernmost transect at Jervis Bay would yield the highest nutrient concentrations. However, the results highlighted an apparent temperature difference between the sites without a marked change in nutrient concentrations.

Figure 5(b) provides a clearer picture, where regression equations (derived from the T-N relations in 5(a)) were used to obtain temperatures corresponding to the prescribed nutrient criteria at each location. The results in Figure 5(a,b) suggest that, along with a decreasing temperature (1-2°C) of slope-water nutrient concentrations from north to south, there are decreases in the correlation of the T-N relationships (R^2 values; Port Stephens=0.75, Port Hacking=0.6, Jervis Bay=0.37). Considering both the southward trends of cooling and increased scatter in T-N relations, this may be explained by an increasing influence of Tasman Sea water on the EAC-advected Coral Sea water from the north.

To further investigate latitudinal bottom-water temperature differences we considered time series data from the four temperature mooring locations during 1997/98 (see Figure 1). Figure 6 shows the temperature frequencies for thermistors 2m off the bottom at the Port Stephens (PS03, PS02), Port Hacking (PH01) and Jervis Bay (JB01) mooring locations in ~60m of water. Applying the $\leq 14^\circ\text{C}$ slope-water criteria to these distributions shows bias, indicating negligible slope-water presence at Port Stephens. This contradicts frequently observed phytoplankton responses during the spring/summer season in this location (Murray and Suthers, 1999).

Temperature Frequency at Port Stephens, Port Hacking and Jervis Bay Moorings (July'97 to May'98)

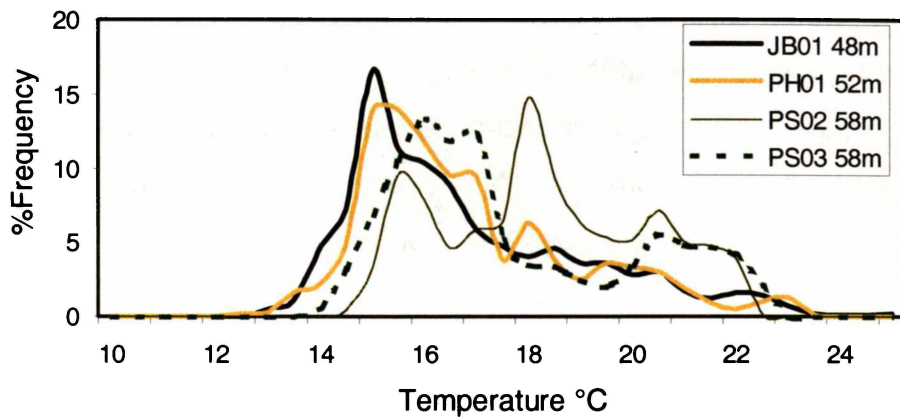


Figure 6: Temperature frequencies for thermistors 2m off the bottom at the Port Stephens, Port Hacking and Jervis Bay mooring locations in ~60m of water.

A -1.5°C offset in the major frequency peak from Port Stephens (PS03) to Jervis Bay (JB01), supports the trend seen in the transect data in Figure 5. It is worth noting that the climatology of the PS02 site, located to the north of the Port Stephens promontory, is markedly different as it is frequently in a direct EAC stream, rather than influenced by the secondary eddy field. PS03 shows a remnant peak in the warmer temperature range, although it is still dominated by the cooler water peak reminiscent of the southern sites.

These alongshore differences also may question whether the source of slope-water received at the coastal sites is locally derived or advected from dynamics occurring further upstream on the shelf. A latitudinal comparison of temperature-nutrient relations in source slope-water beyond the NSW shelf-break, was undertaken by Lee et al (2000a). The work indicated a general southward cooling trend of $\sim 1^{\circ}\text{C}$ for source slope-water (over 5 degrees latitude), supporting claims made here, although this result was complicated with internal variations of up to $\pm 0.5^{\circ}\text{C}$.

An alongshore adjustment of slope-water temperatures, using the T-N relationships from the Jervis Bay and Port Stephens transects in Figure 5(a,b), would provide values more consistent with observations of upwelling frequencies at the Port Hacking site and regional dynamics from SST imagery. Although alongshore, southward trends of 1-2°C are apparent over a 300km stretch, a precise and incremental adjustment along the NSW shelf is beyond the capabilities of the data presented here.

Algal studies

A selection of CTD and water sampling data from the 1978-79 and the 1997-98 twelve-month studies at PH100 are summarised in the adjoining contour plots in Figure 7. As defined in previous work by Newell (1966), Hahn et al (1977) and Hsieh and Hamon (1991), the seasonal patterns evident from the temperature records are reflected in the nutrient levels. In particular the occurrence of high nutrients is well matched with the introduction of cooler water in bottom-waters. A clear biological response to the main slope-water intrusions is indicated in Figure 7 from chlorophyll-a concentrations and counts of a dominant dinoflagellate (*Noctiluca*) measured at the PH50 site by Dela-Cruz et al (1999).

It would therefore be expected that background long-term variability in physico-chemical characteristics of the water column from one year to the next would be reflected in the abundance, distribution or succession of plankton. For example, a tropical species *Trichodesmium spp.* is sensitive to water temperature, so it is not surprising that its distribution in the 1997-98 sampling was limited to water >23°C in the surface mixed layer.

On comparing the two sampling years of 78/79 and 97/98, several differences become apparent. With reference to Figure 7 and Figure 11, it is evident that the 1997-98 year is generally warmer throughout the water column from April to September, and in the upper mixed layer in summer.

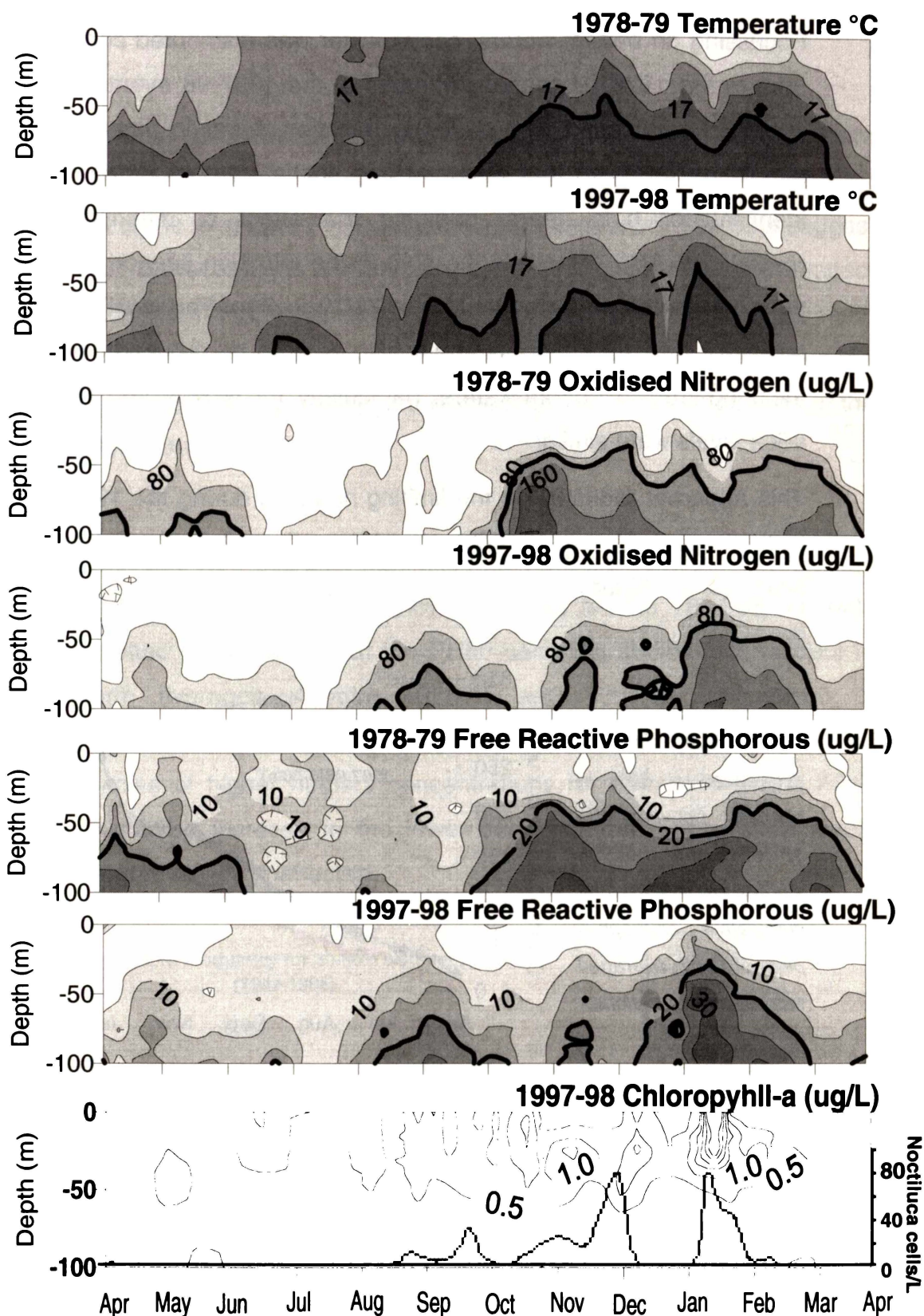


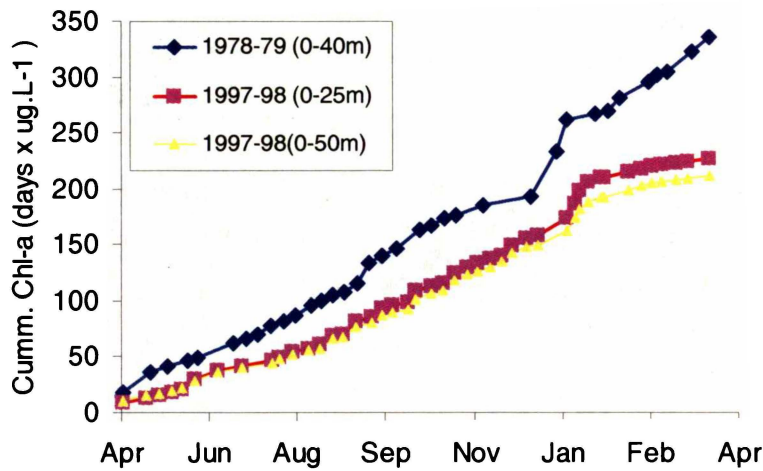
Figure 7: Physico-chemical differences between the 1978-79 and the 1997-98 12 month studies at PH100 are summarised in the adjoining contour plots. The 1997/98 chlorophyll contours respond to the main slope-water intrusions culminating in observed blooms of a dominate dinoflagellate (*Noctiluca*) measured at the PH50 site by Dela-Cruz et al (1999).

Focussing on bottom-waters, cooler water was distributed consistently to 50m in the 1978-79 season, whereas in the 1997-98 events were more sporadic culminating with a strong intrusion event in January 1998. It should be re-stated that temporal and spatial sampling strategies were identical for both years, negating the effect of differing sampling resolutions. Also of note is the shift in the intrusion season (denoted by the 15°C isotherm) from Oct-Mar in 78/79 to Sept-Feb in 97/98. Nutrient levels for the 1997-98 season are also seen to be reduced compared to the long-term in bottom-waters, particularly for NO_x-N and FRP, whilst silica levels were similar.

This apparent reduction in the limiting nutrients during the 1997/98 study (with respect to the 1978/79 study) is reflected in the representative biomass in Figure

8.

Figure 8: Annual differences of 30% in biomass between the 1978/79 and 1997/98 studies are indicated by cumulative chlorophyll plots of depth averaged sample concentrations.



Cumulative plots of chlorophyll concentrations for the two studies (taken as concentration x sampling interval) estimate a total annual difference of ~30%. The 1978/79 chlorophyll-a data from Hallegraeff (1981) was provided as a 0-40m average, and sampling in 1997/98 was at 0, 10, 25 and 50m, so the 1997/98 results are provided as both the 0-25m and 0-50m average. The difference between the 1997/98 plots was small at only ~10% of the difference between the 1997/98 plots and the 1978/79 plot, so the algal response appears to be significantly reduced during the 1997/98 season.

Temperature distributions for bottom-waters (at 30-50m depth) from 1997/98 and 1978/79 sampling at PH50 are shown in Figure 9(a) with respect to the long-term PH50 bottom-water distribution. The data suggest the 1997-98 record was anomalously warm (offset by $\sim 1^{\circ}\text{C}$) with respect to the long-term PH50 averaged annual cycles at 50m. Although the main frequency peak for the 1978-79 bottom-water temperatures exceeded the long-term average occurrence, the distribution was similarly centred at the same temperature peak.

To investigate how this shift may affect or translate to nutrient levels, the bottom-waters (30-50m), frequency anomalies for the 1997-98 nutrients were plotted in Figure 9(b) at the PH50 sampling station with respect to long-term averages. As the 1978/79 and 1997/98 comparison of contoured nutrients in Figure 7 suggested, the 1997/98 data had reduced frequencies of higher nutrient concentrations for both $\text{NO}_x\text{-N}$ and FRP, and a marked increase in the lower concentration range. Silica levels remained relatively unaffected.

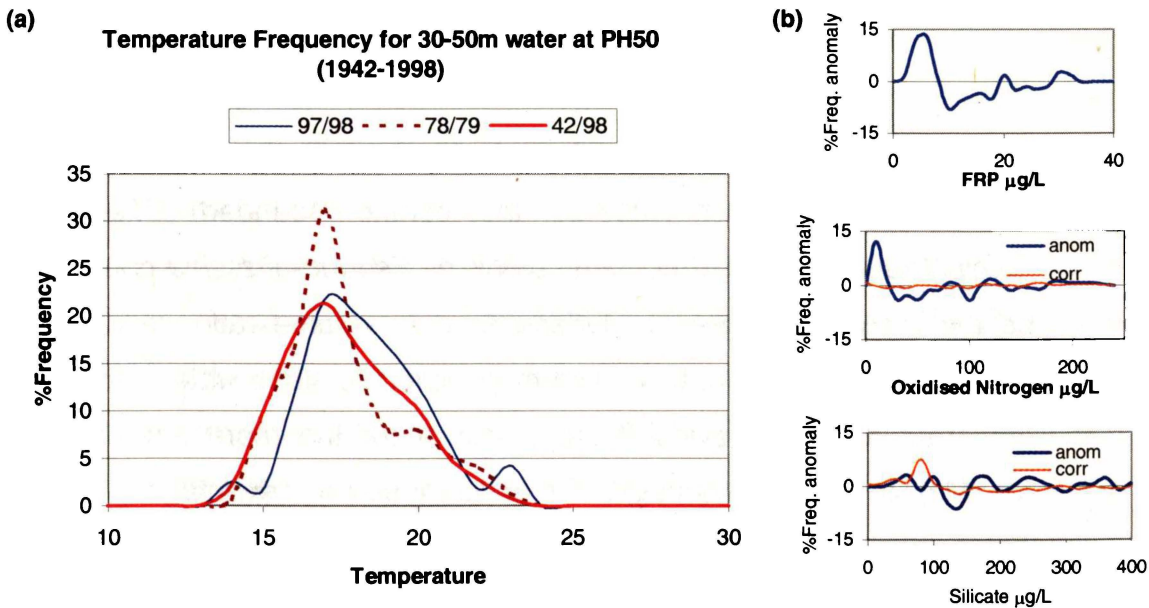


Figure 9: (a) Temperature distributions and (b) frequency anomalies of nutrients at PH50 for bottom water (30-50m) are shown for the 1997/98 sampling season with respect to the long term data set.

The corrections we adopted (from Airey and Storey, 1987) for the NO_x-N and silica long-term data are compared in Figure 9b as the “correction anomaly” to indicate whether the corrected or uncorrected data would bias the result of the frequency anomaly from 1997/98 to long-term comparisons. The correction anomaly for underestimated silica levels (during 1972-1984) provided in the plot, indicates any anomaly for 1997-98 is within this noise level. In contrast the correction anomaly for NO_x-N is negligible with respect to the anomaly for 1997-98 conditions.

Algal Abundance and Diversity

Whilst a general reduction in nutrient concentrations and overall biomass is apparent for 1997/98, it is interesting to note that the algal diversity, and abundance were similar for both periods (Ajani et al, this volume). These seemingly contradictory observations may be due to the predominant type of diatoms that were present in the two sampling years. The reduced NO_x-N and FRP concentrations, and more episodic nature of the intrusions in 1997-98 (cf 1978-79), may have an important influence on the phytoplankton species composition, favouring species that had competitive advantages in both growth and reproductive phases.

In 1978-79 the pennate (elongated) *Pseudo-nitzschia* were most prevalent, whereas in 1997-98 the centric (rounded) *Thalassiosira* dominated. So reduced concentrations of *Pseudo-nitzschia* could simply be the result of its greater surface area to volume ratio, resulting in a difference in nutrient uptake. The more episodic slope-water intrusions of the 1997-98 may provide the opportunity for the more efficient shape (centric) to take advantage. Other competitive advantages, such as *Thalassiosira*'s ability to form large amalgams once in large numbers, may be an important factor in reducing grazing from predators. With respect to the 1978/79 study, Ajani et al (this volume) notes the unusual abundance of *Thalassiosira* was accompanied by a year-round presence of *Noctiluca scintillans*, culminating in blooms of unprecedented proportions in January

1998. *Noctiluca* has been cited by some as a cultural eutrophication indicator in coastal waters (Porumb, 1992; Huang and Qi, 1997), whereas other studies suggest they occur in regions of major upwelling (Elbrachter and Qi, 1988). Dela-Cruz et al (1999) also notes the proliferation of *Noctiluca* in 1997/98 off Sydney dominated 80% of the total zooplankton population suggesting ramifications further up the food chain. It is important to note the major blooms of *Noctiluca* in September/October 1997 and January 1998 succeeded blooms of *Thalassiosira*. Experiments with a range of dominant diatom and flagellate species by Buskey (1995) have indicated *Thalassiosira* is the preferred food for *Noctiluca*. The unprecedented levels of *Noctiluca scintillans* could therefore suggest it was merely responding to the “unusual” predominance of *Thalassiosira*.

When considering nutrients and the phytoplankton response, it is also important to investigate their relative concentrations with respect to favourable growth in phytoplankton population. Literature cites the Redfield ratio (Justic et al, 1995) of 16:16:1 for bio-available Silica:Nitrogen:Phosphorous as the idealised ratio of nutrients for optimal phytoplankton growth. Deviations from this ratio indicate limiting nutrients (e.g. a condition where the ratio is 10:16:1 would be silica-limited). In many coastal regions that are impacted by anthropogenic nutrient inputs (mainly as phosphorous and nitrogen), this silica-limited condition can occur favouring the growth of dinoflagellates over siliceous diatoms. A study by Hodgekiss and Ho (1997) on dinoflagellates focussed on the N:P ratio (16:1) where reduced values favoured particular species such as an optimal ratio of 8-14:1 for *Noctiluca scintillans*. Looking at the PH50 and PH100 data within an annual cycle and as a time series, NSW coastal waters are NO_x-N limited with average N:P ratios of ~8, suggesting conditions favour *Noctiluca*. Ratios over the long-term records exhibited no significant change but, seasonally, ratios approached the optimal Redfield N:P value during summer in bottom-waters (>40m), reflecting a seasonal dependence for enhanced phytoplankton activity. Whilst the less than ideal NO_x-N values may favour *Noctiluca*, silica levels are in

abundance with respect to NO_x-N and therefore do not limit diatom proliferation.

Seasonal Trends and ENSO

The seasonal trends in phytoplankton patterns observed by Newell (1966) and Hallegraeff (1981), may be controlled by the physico-chemical fluctuations in the annual cycle. Figure 10 shows averaged annual cycles at PH50 for temperature and oxidised nitrogen. Similar patterns are seen at the PH100 station. Of note in the sinusoidal temperature cycle is a propagating seasonal lag of 2-3 months through the water column, and the suggestion of a secondary minimum in late summer at 40 and 50m depths in February (probably associated with summer upwellings). The NO_x-N plot indicates a 2-layered water column with a surface water (0-10m) nutrient peak in August and a bottom layer (40-50m) peak in February. This behaviour was also apparent for FRP and silica. These periods of increased nutrient levels coincide nicely with observations of early spring and late summer peak bloom periods by Newell (1966) and Hallegraeff (1981).

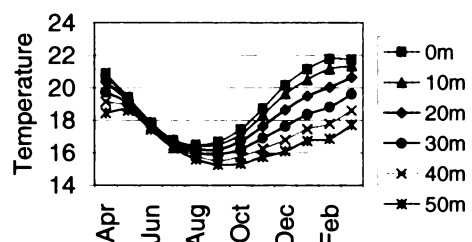
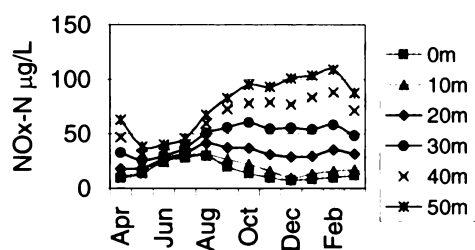


Figure 10: Average annual cycles at PH50 for temperature and oxidised nitrogen indicate lagged seasonality through the water column, surface nutrient peaks in early spring and bottom-water nutrient peaks in late summer.

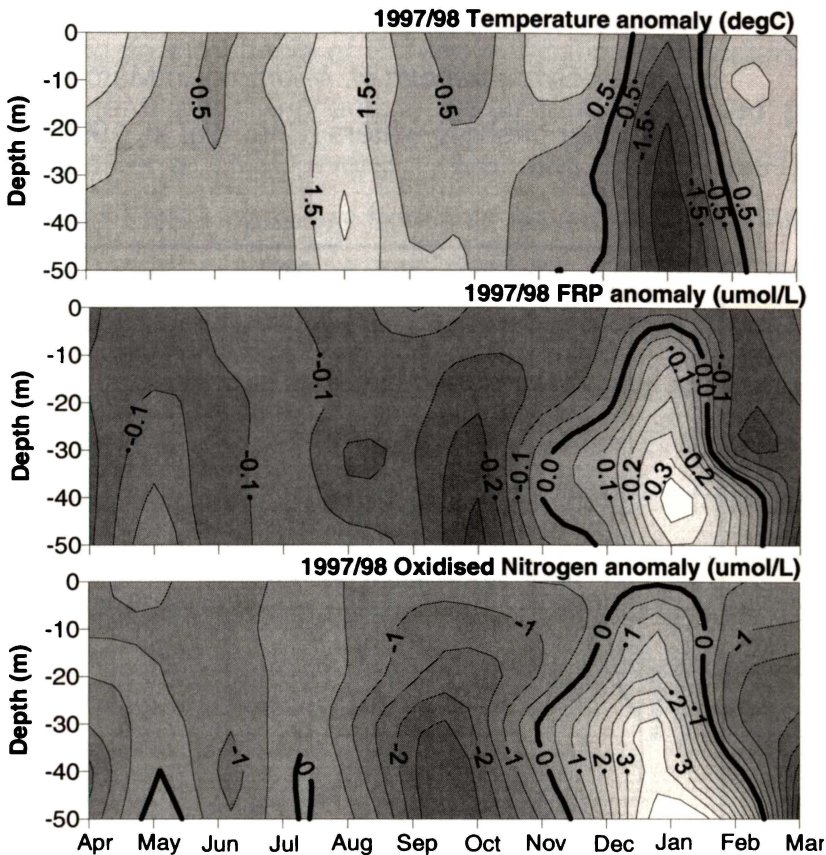


The 1997-98 season is compared to an averaged cycle in Figure 11 for temperature, NO_x-N and FRP. In general the entire water column experiences anomalously warm conditions of up to 1.5°C, although conditions surrounding the prolonged upwelling in January 1998 suggest an unusually cold event. NO_x-N and FRP levels (in more conservative µmol/L units) follow this pattern with generally reduced levels of 1µmol/L

(14µg/L) and 0.1µmol/L (3µg/L) respectively occurring throughout the year, but exceeding the average for the January 1998 upwelling.

Figure 11: Monthly averaged 1997/98 anomalies at the PH50 site with respect to the long-term record.

Climatically, a difference between the two sampling years and the long-term averages may be the presence of a strong El Niño



during 1997-98, whilst normal conditions prevailed in 1978-79. Sprintall *et al* (1995) suggest that during the set-up of an ENSO event, warm water from the tropical SW Pacific drains into the Tasman Sea causing anomalously warm conditions. A warm temperature anomaly was previously experienced in 1991, associated with the set-up of the ensuing 1992 ENSO (Lee and Pritchard, 1997). Allan et al's (1997) long-term SST anomaly data (1872 to present) indicated that, although ENSO conditions generally refer to anomalously cooler conditions in the western Pacific, anomalously warm conditions are often experienced in the coastal region of NSW extending across the Tasman to New Zealand.

The 1997/98 ENSO affected a similar warm anomaly off the NSW coast in December-January that was progressively tracked across the Tasman to New Zealand in February-March (Murphy and Uddstrom, 1998). The anomaly off NSW coincided with the unprecedented blooms of *Noctiluca*

scintillans and *Thalassiosara* in January 1998 (see Figure 8), that prevailed for a month and extended along the entire 300km stretch of the study region. More detail on this event can be found in Lee et al (2001b). The anomalous conditions in New Zealand coincided with a toxic algal bloom of *Gymnodinium cf. Mikimotoi* in March 1998 that was sourced from the warmer offshore waters (Chang et al, 1998).

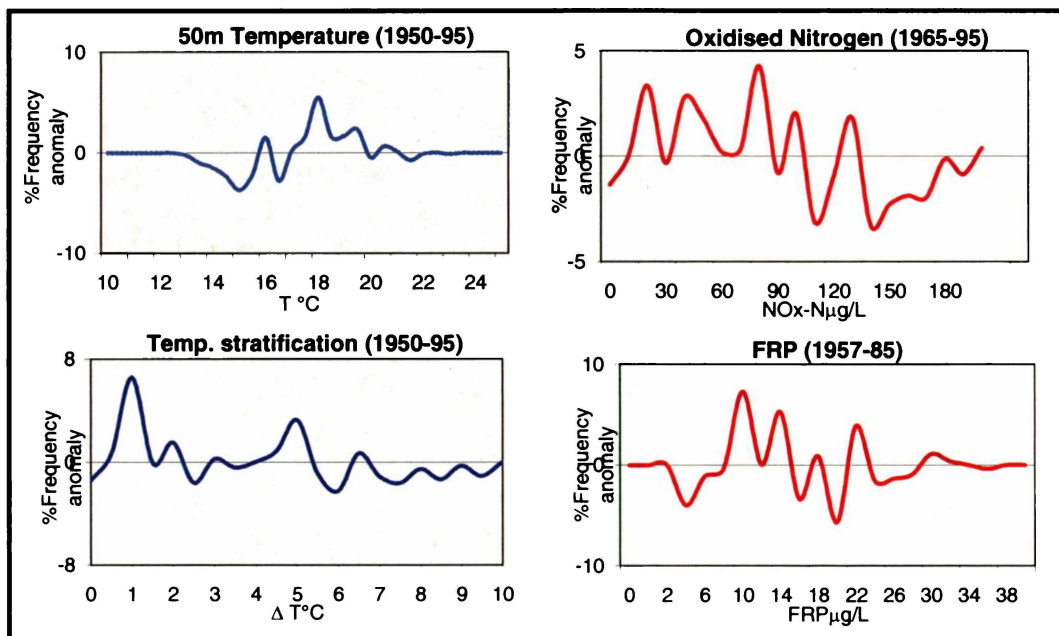


Figure 12: Distribution anomalies of 50m temperature, temperature stratification and bottom-water at the PH50 site for ENSO with respect to non-ENSO periods.

Nichols (1985) indicates 40% of rainfall in South Eastern Australia can be affected by ENSO oscillations, and the 1997/98 sampling period undertaken during ENSO was no exception, experiencing up to 50% less rainfall than the average (Australian Bureau of Meteorology data). Lee and Pritchard (1999) indicate that only during flood conditions do catchments within the study region contribute significant nutrient loads (four-ten times greater than ocean ambient) to the ocean. Such conditions in these coastal catchments were negligible for the study period and, as surface signatures were not observed in the coastal waters, this component did not comprise a significant nutrient input and was, therefore, not

considered as a contributor to the atypical blooms experienced in coastal waters.

It is instructive to investigate the effects of El Niño in local coastal waters, by assessing the long-term physico-chemical parameters measured at Port Hacking over a number of ENSO events. Hsieh and Hamon (1991), had previously assessed ENSO episodes from this record (as 18 month cycles) using EOF analysis and found anomalies of 1/3-1/8 of the temperature (+ve) and nutrient (-ve) signal associated with ENSO. For our assessment, data was collated into periods of El Niño, La Niña and “normal” years. Short “normal” periods of 1-2 years between El Niño and La Niña gave highly variable climatic patterns and were removed from the data-set. Grouped “normal” conditions of three years or more (14 years in total since 1957) were retained for comparison with ten ENSO events. To provide comparison to the 1997/98 study, the years were similarly defined as April to April.

Frequency anomalies generated in Figure 12, compare the distributions of temperature and nutrients in ENSO events with respect to the blocked normal conditions. The PH50 50m temperature frequency anomaly results in Figure 12, show that ENSO favours bottom temperature between 17 and 20°C, and reduces the frequency of 13-17°C (i.e. cooler) temperatures. Oxidised nitrogen concentrations in bottom waters <100µg/L are enhanced (+12%) but those >100µg/L (as typified by concentrations in slope-water) are reduced (-12%). Although results for FRP are more erratic, there is a net -5% anomaly for concentrations >18µg/L and a net +5% anomaly for concentrations <18µg/L. Also of note is the favouring of less stratified conditions throughout the water column during ENSO, reflecting less dynamic conditions (a reduced influence of the EAC). With reference to Figures 7 and 9, all these features are apparent in the 1997-98 record.

The anomalies of averaged annual cycles of ENSO with respect to non-ENSO years are shown in Figure 13 for temperature and nutrients. With reference to 1997/98 anomalies in Figure 11, a comparison of the 12-month sampling season in 1997/98 and effects of ENSO on parameters in the coastal water column (Figure 13) show similar shifts with respect to long-term conditions. ENSO anomalies for temperature (+1°C), NO_x-N (-20µg/L) and FRP (-5µg/L) appear to be consistent with the 1997/98 anomalies, whilst results from the earlier study in 1978/79 were in line with long-term averages. Curiously the cold, nutrient-rich anomalies seen in late summer of the ENSO averaged annual cycle, were also mimicked in the 1997/98 summer when atypical blooms of *Noctiluca scintillans* and

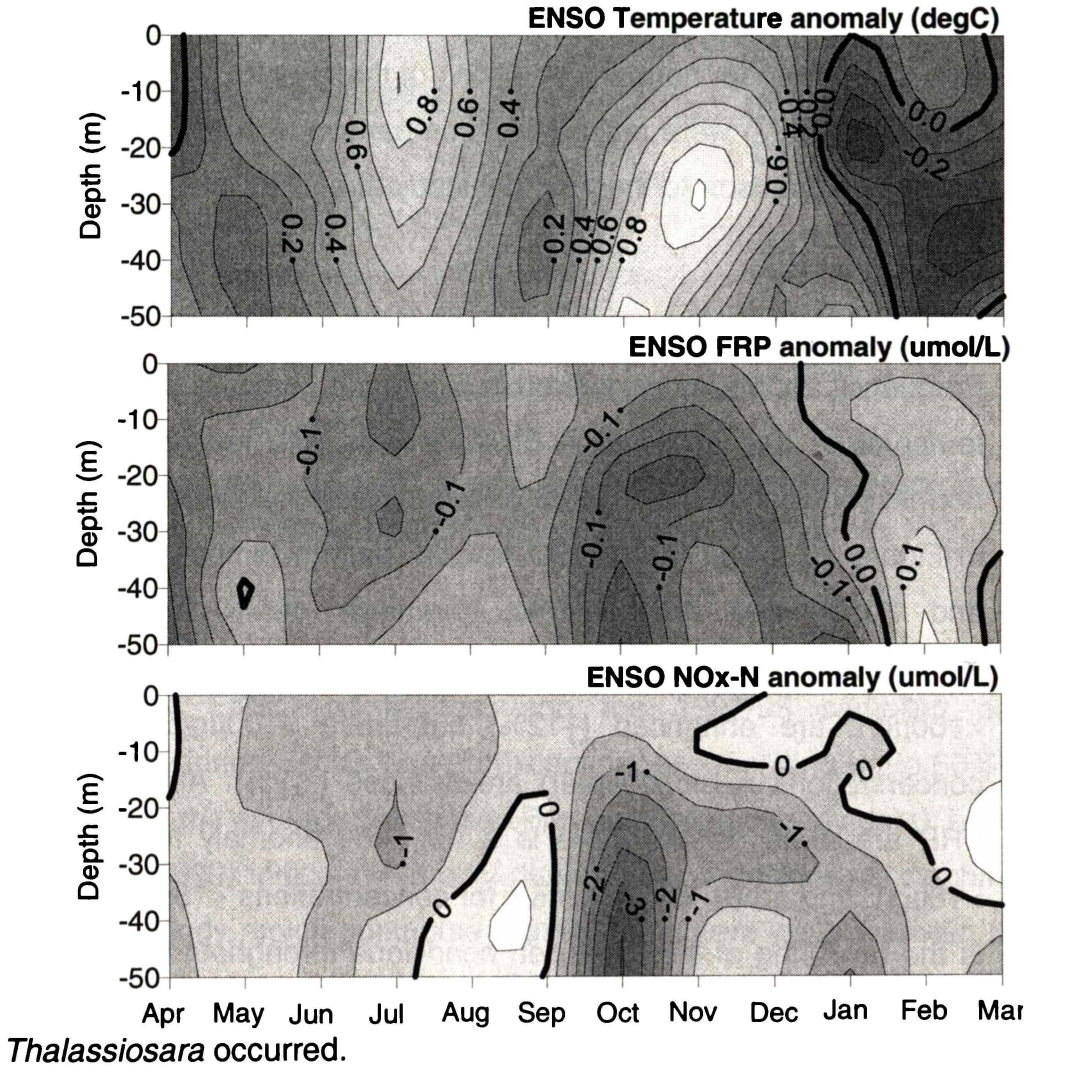


Figure 13: Monthly averaged ENSO anomalies with respect to long-term data from the PH50 site.

It is therefore important to account for these climatic effects when considering observations of change in the phytoplankton populations during and between sampling programs. Looking at the spring bloom season when ENSO promotes a warm, nutrient-poor water column, algal studies from a number of spring seasons provide some support for this claim. Figure 14 compares five non-ENSO spring sampling seasons with the 1997 spring (CSIRO database). T-S and FRP-NOx data indicate that conditions in the 1997 spring were at the warmer and nutrient-poor end of the range experienced in earlier non-ENSO years. A comparison of the presence, absence and abundance of the diatoms *Pseudo-nitzschia* and *Thalassiosira* indicates that 1997 was the only spring where *Thalassiosira* was clearly in abundance and outflanking *Pseudo-nitzschia*.

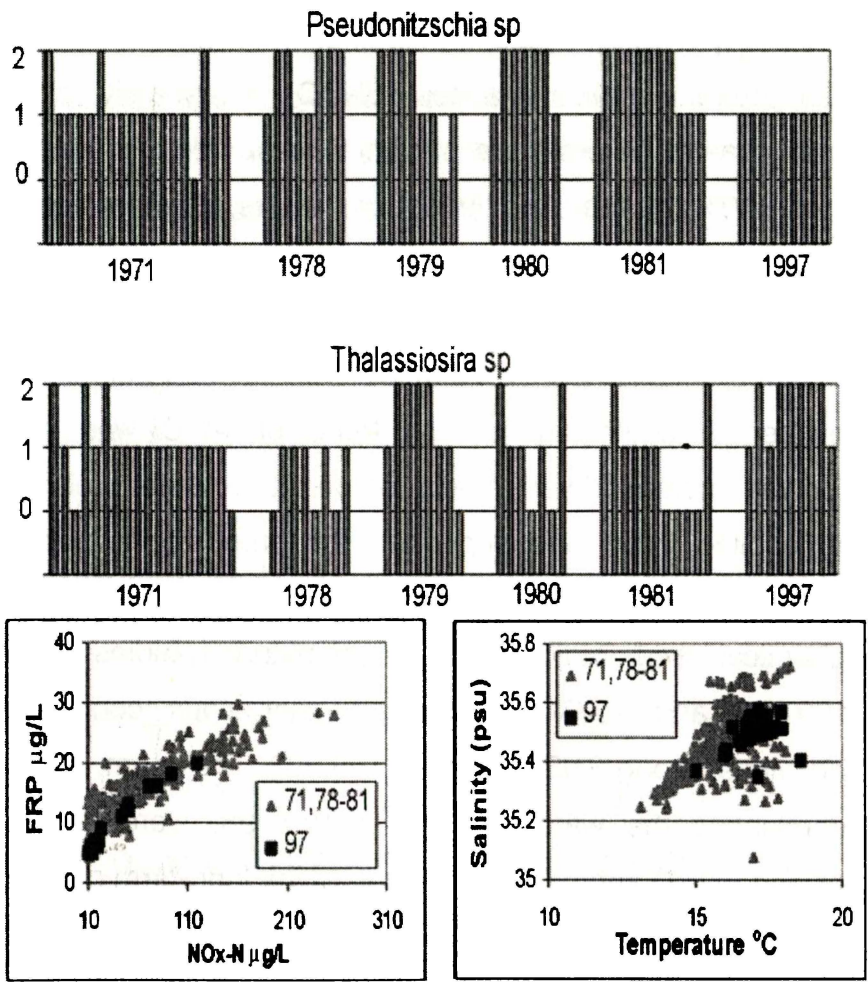


Figure 14: Spring bloom sampling for five years with respect to the 1997 spring for dominance of prevailing diatoms *Thalassiosira* and *Pseudo-nitzschia* (0=absent, 1=present, 2=abundant), and the corresponding physico-chemical conditions.

Conclusions

The long-term (1942-1998) physico-chemical records off Port Hacking, Sydney, were tested for spatial and temporal sampling bias with companion time series records (ORS and PH01 mooring) in the region. We found the effect of not sampling during “bad” weather (wind > 10 m/s) within a continuous record, to be negligible when compared to all-weather conditions. Although the two time series records were well correlated, differences in phase and temperature minima (of up to 1°C) indicated alongshore variability at scales approximating the local Rossby radius.

With the confidence in the data outlined, we investigated the records with well-established temperature and nutrient slope-water criteria, and examined the slope-water signals on the shelf in relation to both seasonal and the long-term climatic variances (ENSO). Seasonally, slope-water intrusions in coastal waters were shown to occur during spring to late summer for <10% of the time in bottom-waters. Temperature-nutrient relations satisfying the well-established criteria at Port Hacking, were questioned when applied to transect data (1995-97) collected from a 300 km section of the NSW shelf. Adopting established nutrient thresholds for slope-water, a southward cooling trend of ~1°C was evident in conjunction with increased variance in temperature-nutrient relations. The southward cooling trend was supported by temperature mooring data collected during 1997/98 over the same study region. Short-term physico-chemical and biological (phytoplankton) studies undertaken during 1997/98 and 1978/79, indicated anomalous conditions were associated with a strong ENSO event in 1997/98. The warm, nutrient-poor waters dominating the water column in 1997/98, were shown to be consistent with ENSO anomalies in relation to the long-term conditions.

Anthropogenic signals were probably not resolved in this study and associated investigations due to the predominance of the ENSO signal. In comparing the 1978/79 and 1997/98 records, results contrasted

expectations of 20 years population growth. The 1997/98 record countered typical cultural eutrophication indicators, with reduced levels of nutrients and chlorophyll-a and no obvious alterations in nutrient ratios or species diversity or abundance. A change in species dominance was, however, noted. The competitive advantages of *Thalassiosira* over the more frequently observed *Pseudo-nitzschia*, and the linked diet with *Noctiluca scintillans*, may explain the atypical blooms that occurred in conjunction with the anomalous physico-chemical conditions of 1997/98. These findings suggest that a good understanding of climatic variance and its local consequences are required when attempting to resolve impacts on a coastal system with short-term investigations.

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7-3 CHAPTER CONCLUSIONS

In attempting to answer the fourth thesis objective, this paper questioned the long-term records for errors that may compromise its use as a reference source. To ensure the reference data (PH50 & PH100m stations) was valid to assess long-term variance, it was checked for consistency of analysis and compared to ORS time series for adequate sampling intervals. An error manifested as a 1°C shift in the temperature distributions was resolved, but shown to be associated with alongshore spatial differences, rather than due to inadequate sampling to resolve the climatology. The ENSO signals resolved in the long-term records matched the anomalies seen in the 12-month study (Section 6-3) when a strong ENSO was present. The respective positive and negative anomalies accounted for ~30% of the annual signal for temperature and nutrients. Whilst one goal of the 12-month study was to resolve any plankton differences associated with a ~10% increase in STP discharges (since the prior study in 1978/79), the 30% reduction in nutrients associated with ENSO in the 1997/98 study clearly opposed the long-term trend. Whilst this outcome of the 12-month study was severely compromised by the ENSO signal, the ability to utilise the historical data enabled its understanding. The continued discussion on long-term patterns in the following chapter addresses perceptions of change and places them within the framework of the measured fluctuations and trends.

Chapter 8: Discussion

The aim here is to explore issues and consolidate the thesis in one unified discussion chapter. In particular, the chapter extracts from the previous papers the information needed to address the primary aims of the thesis. Thus, the following sections relate to the four objectives outlined in Chapter 1, as;

1. the comparison/partitioning of The Nutrient Sources,
2. a discussion on The Question of Cultural Eutrophication,
3. quantifying scales from Regional Comparisons,
4. an overview of Long-term Patterns.

New papers not previously discussed in the thesis have been included to provide further enlightenment about the important results and conclusions. In addition, critical results needed to complete the discussion, but not included in the papers, are presented here. Appendix one provides summaries of these associated publications. The discussion here continues the theme structure that has prevailed throughout the thesis. By initial comparison of the nutrient sources, the discussion continues exploring issues associated with the dominant anthropogenic sources and their impact on phytoplankton populations. Drawing upon results from the large study off the NSW coast, comparative studies off the New Zealand NE coast are assessed to indicate the regional coherence of the large scale ocean circulation (South Pacific Gyre) patterns, and as a measure of conditions in a region relatively unimpacted by anthropogenic inputs. Long-term observations and measurements off the NSW coast are finally referenced to provide context of seasonal and inter-annual scales with estimates of long-term trends.

8-1 THE NUTRIENT SOURCES

This section discusses the relative importance of natural and anthropogenic sources that can provide bio-available nutrients to phytoplankton in coastal waters. This exploration incorporates field

investigations, reviews and re-analysis of existing data sets, use of existing near-field plume model results and additional hydrodynamic modeling. This comparison places special emphasis on the introduction and dispersion of nutrients from sewage (ocean outfalls), estuaries (floodwaters) and oceanic (slope water) sources. The partitioning of these sources can be defined the relative signatures of the dominant nutrient species.(e.g. ammonia from outfalls, silica from estuaries, ideal Redfield ratio nutrients from slope-water). However, due to rapid mixing rates in coastal waters, it is often that the physical attributes associated with the inputs from these sources that define their signature and specific effect on phytoplankton populations.

8-1-1 Sewage outfalls

From sewage treatment plant (STP) monitoring referenced in section 3-2, the outfalls provide a continuous source of nutrients to coastal waters that fluctuate with rainfall. The average dry weather flow (ADWF) and peak wet weather flow (PWWF) rates quoted in the summary (Table 8-2), correspond to the 50 and 90%ile loads from annual hydrographs in the STP's. While the results from section 3-2 indicate the dominance of the deepwater outfall loading to NSW coastal waters over all other anthropogenic discharges, it also highlights a dependence on seasonal structuring of the water column. This determines whether the discharged plume reaches the euphotic zone (upper mixed layer) providing nutrients to phytoplankton. During winter months a surfacing plume can occur for ~40% of the time, but the more diluted plume provides lower concentrations to the surface layer. Also, lower temperature and light levels inhibit algal growth, and slope water intrusions are shown from long-term records to be rare. During the summer season outfall plumes are trapped for 90% of the time (Lee and Pritchard, 1996), essentially withholding the nutrient supply from the euphotic zone.

On seasonal scales it appears that the stratification process counters the ability for the sewage plume to supply nutrients to plankton during their peak growth periods of spring and summer. During stratified summer

conditions though, internal waves can momentarily provide a vertical flux of the trapped nutrient store (see section 8-2-1), but the loads are likely to be insignificant for a resulting phytoplankton response. Prolonged events such as slope-water intrusions however would be effective in venting the plume's nutrient store to enable sequestering by phytoplankton. This of course would be complicated by the enhanced nutrients of the intrusion itself. Overturning by downwelling could also effectively introduce the sewage store to the euphotic zone (and nutrients in the re-suspended sediments). But as this scenario is also associated with increased turbidity and turbulence, unfavourable conditions for phytoplankton growth would prevail.

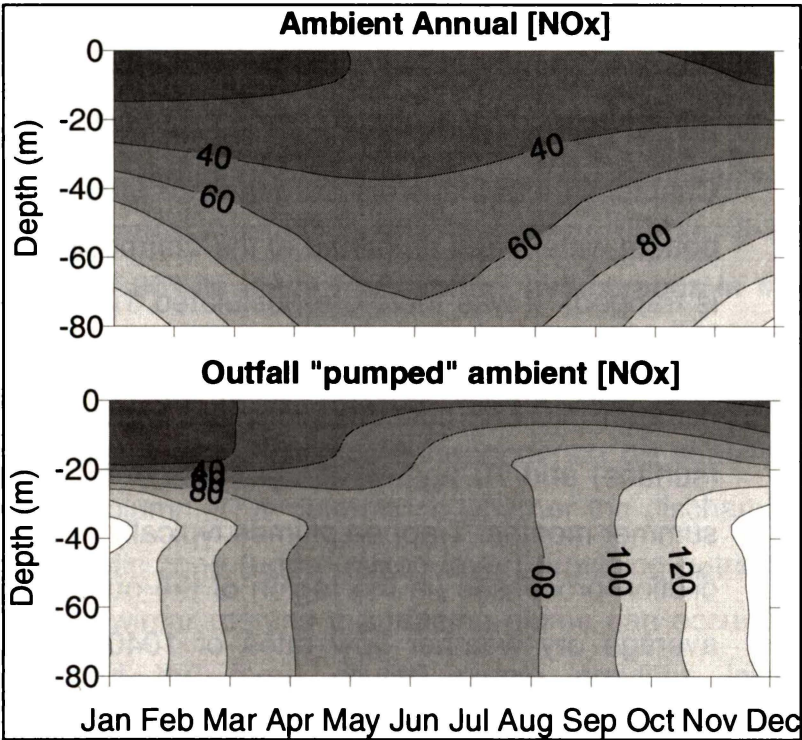
Outfall assessments in Chapter 3 indicated from N:P ratios that these nitrogen limited waters are most prone to phytoplankton growth during spring/summer when optimal Redfield ratios are approached due to the nitrate maximums. It was also shown from earlier studies (presented in Chapter 3) that these discharges were predominantly mixed with ambient bottom waters and entrained to the thermocline (where the sewage plume is trapped). It was therefore postulated that the outfalls may be acting as an ambient nutrient pump, enhancing the seasonal patterns. Oxidised nitrogen (NO_x-N) concentrations are typically stratified between 10 µg/L (surface) and 70 µg/L = 70 kg/ML (bottom) in coastal waters during the summer months. Trapped plumes typically dilute to 1:300 during near-field dilution processes (in the region of the outfall). Therefore employing total average dry weather flow rates of 1040 ML/day for the three outfalls estimate, the vertical flux of ambient NO_x-N is potentially ~20 t/day from the bottom water layer to the sewage plume trap depth. This compares to ~33 t/day of nitrogen (taken as nitrate + ammonia, where typical effluent concentrations of 40 mg/L) released from the three deepwater outfalls. This assumes receiving waters have no diluted effluent. To achieve this, the three outfall's 2 km of diffuser lines (mixing with an assumed 5 m bottom layer) require the ambient current to be greater than 0.15 m/s. From 10 years of ORS data the bottom 52 m currents average is $\approx$ 0.15

m/s and are ≥ 0.15 m/s for 45% of the time, indicating these induced ambient fluxes are probable.

Furthermore, the averaged annual cycle from the PH100m station is used here to estimate an annually pumped load. Figure 8-1 shows the annual NO_x-N concentrations for ambient conditions (prior to outfall commissioning) and the structure when entrained by the outfalls. The entrained structure was calculated using weekly averages of modelled plume dilution and trapping depths (using results from Chapter 3). It should be noted that the estimates for ambient loading are not altered by this effect, the vertical entrainment merely locates higher nutrient concentrations at shallower depths.

Figure 8-1: Average annual cycle of ambient oxidised nitrogen and annual concentrations associated with bottom water entrainment by the deepwater outfalls.

As expected the entrainment is seasonally pronounced, suggesting this



"pump" effect could enhance local and remote upwelling episodes during summer. Whilst this effect does not introduce new nutrients to the coastal ocean it has been incorporated in the summary (Table 8-2) for comparison as a loading mechanism.

8-1-2 Slope-water intrusions

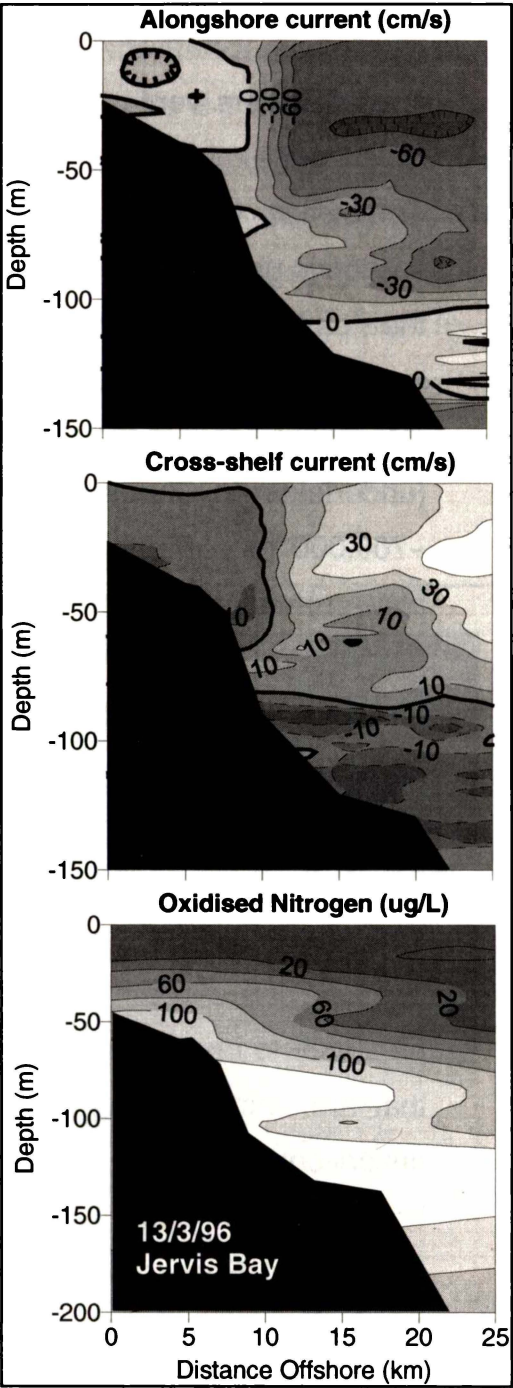
In the study region, the inner shelf was often observed to be the source of nutrients for algal bloom response in coastal waters (Chapter 6). Study findings in (Chapter 4-5) typified the inner shelf as the region where coastal waters vent sub-surface waters (eg isotherm outcropping), often isolating the offshore surface mixed layer from this coastal boundary layer. To estimate the effective ambient loads in coastal waters, this inner shelf section is used for comparison with anthropogenic sources. Dimensions of the Port Hacking transect are adopted as it is an average representation of shelf width in the region, and is also where the dominant anthropogenic discharges occur in the study region. From transect survey measurements (undertaken in Chapter 5), this inner shelf profile relates to an area of $\sim 700,000 \text{ m}^2$. Depth average alongshore currents from the ORS (0.22 m/s) corresponds to a $\sim 20 \text{ km}$ daily advection of this cross-section. For ambient conditions on the inner shelf, depth averaged oxidised nitrogen and dissolved phosphorous concentrations are respectively 60 mg/m^3 and 10 mg/m^3 , and respective daily loads are estimated as 840 t/day and 140 t/day .

The studies in Chapters 4 and 5 have also shown that intrusions of nutrient rich slope-water from the shelf break are the predominant precursor to major algal blooms. These can occur from remote upwellings that are entrained alongshore by the prevailing southward flow, or are driven onshore locally. To estimate loading from these two methods of intrusions, respective along-shelf and cross-shelf fluxes need to be determined. Results from the modelled temperature structures (alongshore dimension) and sampling transects (intrusion thickness and extent), are employed to determine an estimate of the volumes involved in shelf intrusions. The upwellings captured during the 1995/96 summer period in Chapter 5, provide a good data source for these load calculations. It is possible to relate the physico-chemical and water quality data with current dynamics measured by the ADCP during intrusion events.

Figure 8-2 shows that the cross-shelf structure during upwelling conditions typically has an intruding layer of 20-50 m thick associated with onshore fluxes of 0.05-0.1 m/s. This corresponds to intrusion fluxes determined by earlier model simulations of upwelled conditions at Port Stephens and Jervis Bay (Oke and Middleton, 2001; Gibbs et al, 1997).

Figure 8-2 NO_x-N concentrations and ADCP current components measured at Jervis Bay during the 1996 summer relate intrusion volumes with onshore nutrient flux.

Across the inner shelf, these fluxes can be tracked and verified by comparing temperature fronts at cross-shelf station pairs from the thermistor array's 50 m and 100 m moorings (Chapter 4). During intrusion events in September 1997 and January 1998, lags in thermal response between station pairs off Jervis Bay and Port Hacking were clearly evident (Figure 8-3). These lags corresponded to cross-shelf fluxes that ranged between 0.05-0.08 m/s.



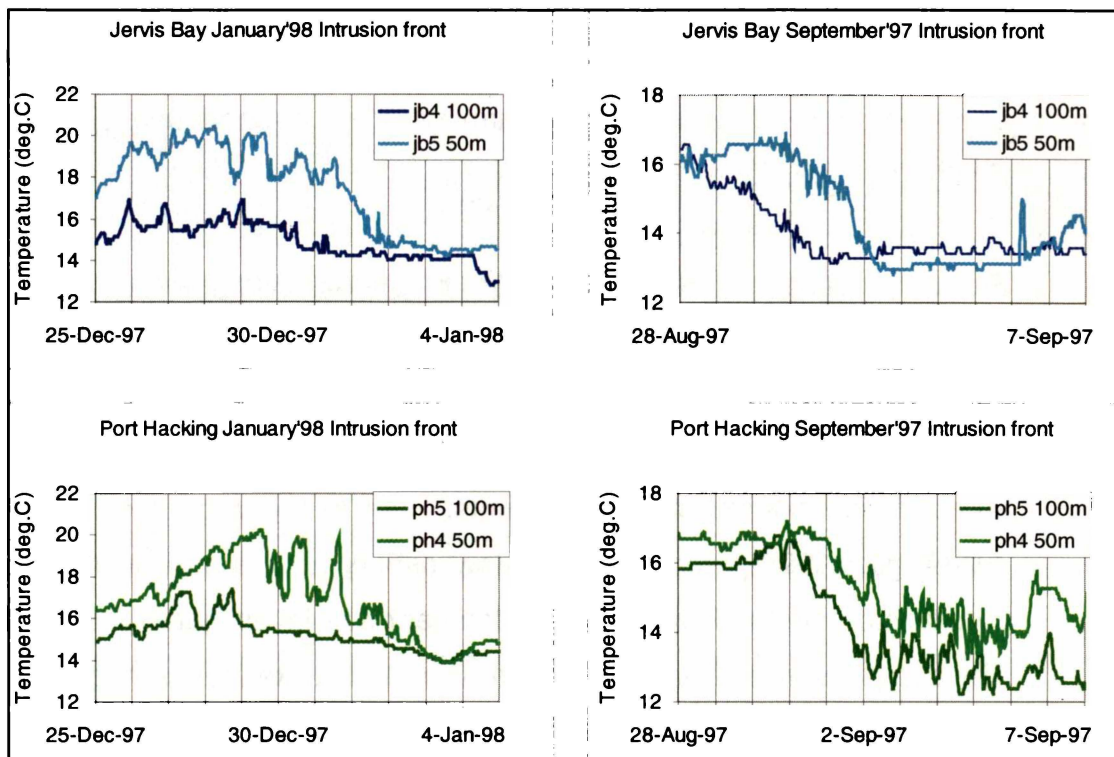


Figure 8-3: Intrusion fronts for September 1997 and January 1998 at Port Hacking and Jervis Bay.

Information from Chapter 4 of modelled temperature structures, supported by thermistor mooring arrays, indicate these upwellings were occurring at alongshore scales of 50-100 km in the study region. The nutrient load associated with this source is estimated by an adopted 20-50 m layer moving onshore at 0.05-0.1 m/s over a 50-100 km section with concentrations of $\sim 100 \mu\text{g/L}$. The summary (Table 8-2) incorporates these ranges in the daily flux of 400-4000 t/day for oxidised nitrogen, and 80-800 t/day for dissolved phosphorous to the continental shelf from the slope.

8-1-3 Estuarine discharges

From the SKM (1998) overview of catchments incorporated in the Chapter 3 studies, total annual loads (in tonnes) to coastal waters were estimated as 1,600 – 7,400 t/yr TN and 160 – 770 t/yr for TP. The high ranges indicate total catchment exports to coastal waters as measured during the July/August 1998 floods from the Hawkesbury and Hunter catchments (section 3-3), while low ranges have included an estimate of nutrient

buffering (according to SKM, 1998). As indicated in Chapter 3, nutrient buffering (or fallout in the estuarine section) is dependant on the establishment and maintenance of the horizontal salinity gradient which can take several weeks to re-establish after a flood event (Lee and Pritchard, 1999; Eyre and Twigg, 1997).

From the onset of the 1995-98 study period, wet weather discharge experiments had been proposed to account for uncertainties regarding discharges to coastal waters (as indicated in the SKM, 1998 data review). These experiments were triggered by monitoring upper catchment river levels during significant rainfall events. Prior to the large flood events of July/August 1998 sampled in the Hawkesbury and Hunter rivers, a small coastal storm in the Hawkesbury catchment was investigated in May 1998. The comparison of this investigation with the Hawkesbury's August floods in Figure 8-4, highlights the necessity of the salinity gradient to be breached to ensure significant input to the coastal ocean.

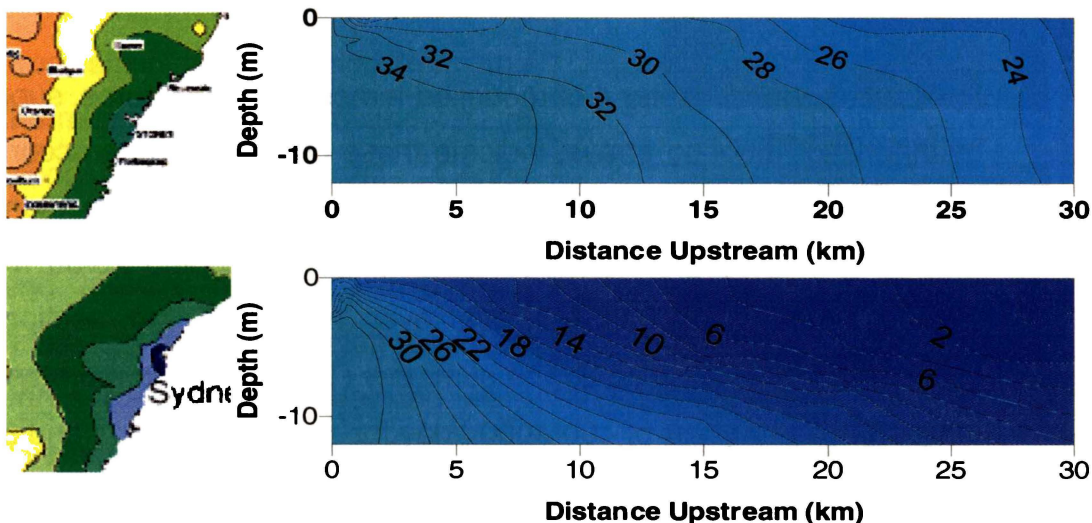


Figure 8-4: Response to coastal rainfall events in May 1998(aqua= 150 mm) and August 1998 (d.blue=250 mm) 1998, shown as upstream salinity (psu) profiles in the Hawkesbury River.

The cumulative weekly falls of up to 150 mm in May'98 barely affected in-stream conditions, whereas the weekly falls of up to 250 mm in August'98 indicated significant discharges of flood waters 3-4 times the ambient ocean nutrient concentration (Figure 8-5).

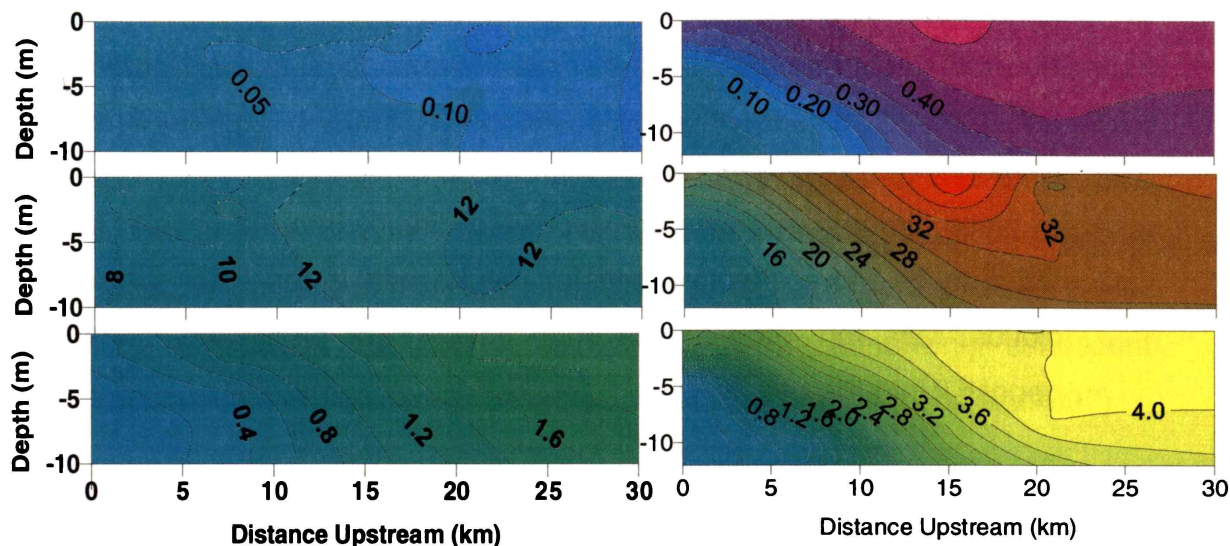


Figure 8-5: Upstream profile of nutrients (nitrate, phosphate and silicate in $\mu\text{g/L}$) in the Hawkesbury River during the rainfall events of (left) May 1998 and (right) August 1998.

These respective floods were monitored at an upper catchment station (Castlereagh), where the May 1998 flood caused a peak level of 2.75 m, whereas in August 1998 floodwaters rose up to 8 m, or some 6m above ambient. These two flood levels corresponded to return periods of 0.6 and 2.4 years respectively. While both floods were within the 90%ile flow condition adopted by SKM (1998), their loads discharged to coastal waters were significantly different.

Characteristics such as stream gradients, channel forms, estuary shape, geology, soils, vegetation and land use. The coastal discharge from each flood event is unique, being a function of these catchment characteristics, combined with the rainfall intensity, its duration and spatial coverage, and background groundwater levels. Nutrient concentrations would also vary according to the temporal proximity of the rainfall events, with an expected increase in load from a “first flush” (after a long period of no rain). So while it is beyond the capacity of this study to address the detail associated with flood events in the region, the wet weather event studies and the SKM (1998) data review do provide a context for comparison of the extremes and averages experienced in the region.

8-1-4 Other sources

Atmospheric

Nutrients are present in the atmosphere as particles and as gases. Some of these airborne nutrients are deposited directly into the ocean ('fallout') but a much more effective transfer mechanism is for water droplets (in clouds, rain, fog, etc.) to scavenge gaseous or particulate matter and deposit it into the ocean.

In some parts of the world, such as the western Baltic Sea, western Mediterranean and the North Atlantic, atmospheric nitrogen is the most rapidly growing source of new nitrogen in seawater (Pelley, 1998). Activities, which promote these increases, include fossil fuel combustion and ammonia vaporisation from manure and fertilisers. Expanding urbanisation, agricultural and industrial activities associated with coastal population growth therefore have the potential to make atmospheric deposition an important source of new nitrogen in coastal waters. The average vertical flux of atmospheric nitrogen to the surface of the ocean can be compared with the average horizontal flux in the upper mixed layer of the water column.

Utilising average ambient concentrations in the surface layer (18 mg/m^3) and average alongshore current (0.22 m/s) the alongshore flux is estimated at $\sim 0.5 \text{ kg/m}^2$ per day for nitrogen (assumed here as nitrate + ammonia). From average annual Sydney rainfalls (3 mm/day) and rainfall concentrations (380 mg/m^3) obtained in Table 8-1, a flux of $\sim 1 \text{ mg/m}^2$ per day is estimated for nitrogen, or $\sim 0.02\%$ of the horizontal flux. Adopting the effective coastal layer ($7 \times 10^5 \text{ m}^2$) previously defined for ambient ocean loads (in 8-1-2), and assuming an effective fallout footprint equivalent to the $\sim 20 \text{ km}$ alongshore daily advection ($1.6 \times 10^8 \text{ m}^2$), the loads are similarly low at ~ 0.1 tonnes. Significant rainfall events (90%iles of 50mm) would increase the atmospheric flux up to $\sim 8 \text{ t/day}$ or $\sim 1\%$ of the daily ambient alongshore flux.

Atmospheric nitrogen (N₂) may also be sequestered to the ocean via nitrogen fixing phytoplankton such as the blue-green alga, *Trichodesmium erythraeum*. In fact, atmospheric nitrogen fixation by *Trichodesmium* appears to dominate nutrient inputs to large areas of the Coral Sea (Furness *et al.*, 1995). But, in NSW coastal waters, *Trichodesmium* is generally present in low densities (Ajani *et al.*, 2001b) and in our cooler waters, nitrogen fixation would be unlikely because only senescent *Trichodesmium* cells would be expected (Hallegraeff *pers comm.*, 1997).

Table 8-1: Estimates of atmospheric deposition (loading) to coastal waters.

Nitrogen (kg/ha/yr)	Phosphorus (kg/ha/yr)	Source
0.6 – 13	N/A	Feth, 1966 – measured in rainwater
6 – 10	0.05 – 0.06	Loehr, 1974 – measured in rainwater
2.56	NA	Carnovale <i>et al.</i> , 1987 – aerial deposition to Port Phillip Bay
~4.6	NA	Based on Ayres <i>et al.</i> , 1987 – typical ('81/'82) Sydney rainwater concentrations of 0.17 mg/L nitrate & 0.21 mg/L ammonia. (Assumes negligible organic N in air; and, average rainfall of 1225 mm/yr).

Sediments

Sediments can act as both a source and a sink for water column nutrients. Few data exist to predict the exchanges of nutrients at the sediment-water interface because limited available data were mainly gathered in enclosed waters rather than in the more dynamic offshore waters. Sediments in our study region are sandy with low levels of nutrients and organic carbon. On the inner shelf (<60 m) sediments typically consist of coarse, clean (<2% mud), well sorted sands while, in the mid shelf region (60-120 m), coarse sands have a higher mud content (patchy 5-20 % mud). These inner and mid shelf sediments have been found to be highly mobile with potential for re-suspension of the top one metre of sediment at water depths of about 30 m and re-suspension of the top 50 cm of sediment at depths greater than 60 m (Schneider and Davey, 1995). Nutrient fluxes at the seafloor

were effectively incorporated in our assessment as an ‘oceanic’ source because fluxes contribute to (or reduce) bottom water nutrient stocks. By considering sediment-water nutrient fluxes in this way we have assumed that the anthropogenic fraction of any previous accumulations of nutrients in the sedimentary column either remain biologically unavailable or contribute insignificant amounts of anthropogenic nutrients to bottom waters. This assumption is consistent with our consideration of nutrient loadings from ocean outfalls and estuaries (catchments) where, for the purpose of this assessment, we assumed no sedimentary sink despite the fact that both types of discharges are typically high in suspended solids.

8-1-5 Overview

The loading characteristics of all the inputs developed in the preceding debates are summarised in Table 8-2, focusing on the limiting nutrient, nitrogen.

*Table 8-2: Comparison of nutrient sources for nitrogen (taken as ammonia + nitrate) as averages and events. (Note: *remote upwelling flux represented as event ocean ambient).*

Component	[Avg.] (µg/L)	Load (t/day)	[Event] (µg/L)	Event load (t/day)	Event (%)	Notes
Sewage Outfalls	40000	33 (ADWF)	45000 (PWWF)	83	10	N:P ratios changed
Ambient Nutrient "pump"	78	20	150	40	5	Optimal location
Atmosphere	NA	NA	380	0.1-8	10	Footprint variable
Sediment Re-suspension	NA	NA	NA	NA	NA	Too deep to affect euphotic zone
Estuary			160	4-20	10	Turbidity could shade plankton
Ocean ambient	60	840	100*	1100*	5	Depth av.
Ocean upwelling	-	-	100-150	400-4000	5	

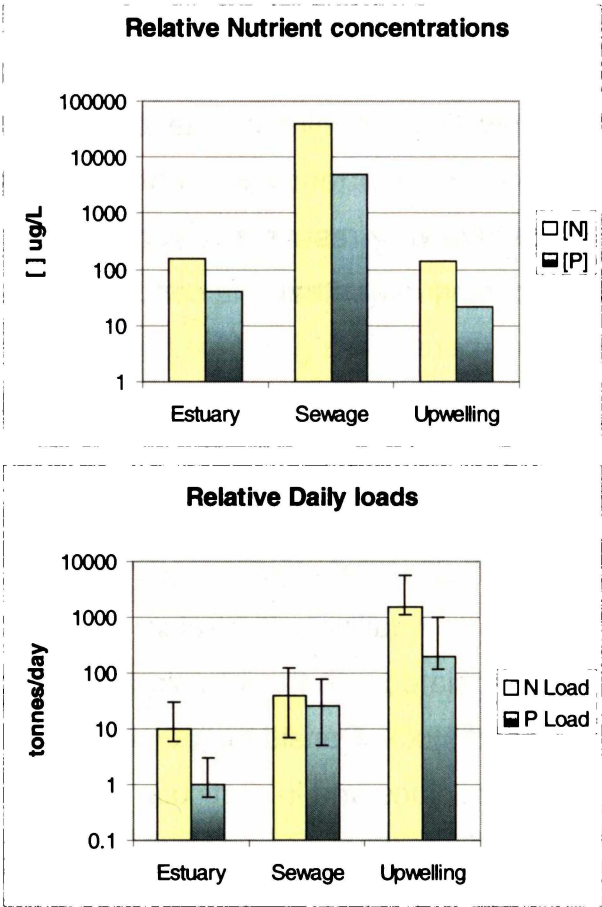
When comparing nitrogen loads coastal discharges from estuaries and sewage outfalls, and upwelled intrusions, accounts for the majority of

quantifiable inputs. Consideration of these major components are summarised further in the adjoining plots in Figure 8-6, as the means and relative ranges associated with each source. Although sewage inputs are clearly providing the highest concentrations to coastal waters, when the daily load from the major sources are considered, nutrient supply from upwellings dominate. The seasonal patterns of phytoplankton blooms that were shown to be well correlated to upwelled intrusions throughout this study (from results in Chapters 4-6), are therefore more sensitive to the loading rather than the concentration of nutrients.

Parslow (Pers. comm.) has suggested that nutrient concentrations can reach saturation levels for optimal plankton activity, and hence the excessive concentrations associated with the sewage outfalls may be ineffective in nudging large numbers of plankton required to achieve bloom status. Intuitively it is also obvious that the increased volume of water associated with the intrusion loads would impact on a larger phytoplankton seed stock. Considering typical time lags for plankton to respond in bloom proportions and in particular for the successional response of *Noctiluca* to diatoms, the various processes that subsequently accumulate plankton near the coast could then concentrate the product of this larger source load. Given this focus on the oceanic source, and the public sensitivity of coastal water quality issues, the continued discussion in 8-2-1 explores the accumulation processes in coastal waters that can enhance the impact of algal blooms.

Figure 8-6: Relative nutrient concentrations and daily loads from the major sources in the study region. Note that daily load estimates are given with ranges representing the degree of variance in the source supply.

1. Average daily Estuary loads accounts for ranges of total export from the catchment to adopted buffering values from SKM (1998).
2. Average daily sewage discharges ranges from Dry weather flow to Peak wet weather flows.
3. Ranges of Upwelling loads are based on scales determined during the study (1995-98) and from moored records and modelled data 1990-1998 (Lee et al, 2002).



8-2 THE QUESTION OF CULTURAL EUTROPHICATION

Eutrophication is defined as the process of nutrient enrichment in aquatic ecosystems such that the productivity of the system ceases to be limited by the availability of nutrients. This may occur naturally over time, but can be accelerated by human activities such as sewage discharge and diffuse runoff, which causes a condition termed 'cultural eutrophication'. The result can be a system whose natural nutrient composition has been altered, causing conditions for the residing phytoplankton population that may or may not favour their abundance. The phytoplankton response is used as an indicator of cultural eutrophication by recording a change in abundance, species diversity, or a shift in species dominance. As the report of phytoplankton blooms is the endpoint by which public concern is raised, it is important to also understand the processes that impact on a bloom in coastal waters. An overview of naturally occurring accumulation and mixing processes that can assist in the manifestation of a coastal algal bloom, therefore follows as an introduction to the discussion on anthropogenic influences in the coastal zone.

8-2-1 Coastal Impact

From time to time natural convergence zones form in the ocean, often in areas which are pre-disposed to such phenomena. Accumulation usually occurs when convergent flows bring particles, such as plankton, together. If particles are sufficiently buoyant, they will remain at the surface where the two water bodies converge while the convergent water descends usually in the *downwelling* arm of a three dimensional circulation cell. Abundances of plankton may be 10 to 1000 times greater in these zone of convergence than in surrounding waters (Kingsford 1990). Therefore, accumulations of particles in these zones may be sufficiently dense to be visible in their own right or they may affect the surface tension of the water to such an extent (for example, through the surfactant properties of their breakdown products) that they are visible, often as lines in the ocean. Of course these zones of convergence concentrate both plankton and pollutants. Various processes can be responsible for convergence.

Current shear between two different water masses may be sufficient to establish a zone of convergence.

Operating at a larger scale, this effect of shear was observed with SeaWiFs imagery during the January 1998 responsive studies (Chapter 5-6), where East Australian Current water impinged on a cooler coastal water body (see Figure 8-6) forming fronts. Local topography may make particular areas more prone to convergence through the establishment of re-circulation zones in the lee of promontories. On a large scale this was evident as the back-eddy in the lee of Port Stephens that developed from the EAC frontal feature in Figure 8-7.

On smaller scales turbulence caused by coastal topography is manifested within a *coastal boundary layer* as a counter current to the main oceanic flows. Observations during the project have shown that for periods of a week or weeks after flood or storm events a turbid *coastal boundary layer* prevails alongshore retaining flood discharges.

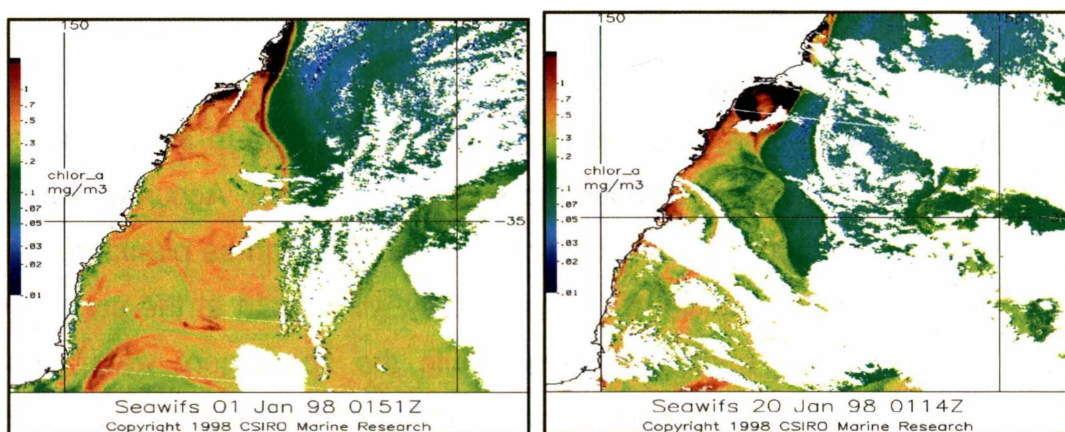


Figure 8-7: SeaWiFs images of chlorophyll-a reflectance during January 1998 indicate phytoplankton abundance accumulating on a coastal EAC front (left), and (right) later the majority of the accumulated phytoplankton had been captured by the backeddy formed in the lee of Port Stephens.

Similarly more localised shear can occur at the mouths of estuaries (see Figure 2-5 – Chapter 2), and feed into this coastal layer during flooding periods when the fresh discharges override the estuary's salinity gradient. Likewise, wind effects can lead to the establishment of *Langmuir Cells* and

lines (*windrows*) which run parallel to the direction of the wind. The *Noctiluca* bloom off Sydney in 1996 manifested itself in windrows as it threatened a major bathing beach (Figure 8-8) causing great public concern.



Figure 8-8: Convergence lines of Noctiluca offshore off a popular Sydney bathing beach (photo courtesy of NSW EPA, Beachwatch, 1996).

Other phenomenon, such as the passage of *internal waves*, may set up similar cells but in this case lines of surface level convergence run perpendicular to the direction of propagation. Their interest however is more in their ability to enhance the vertical flux of nutrients that typically adhere to a vertical concentration gradient.

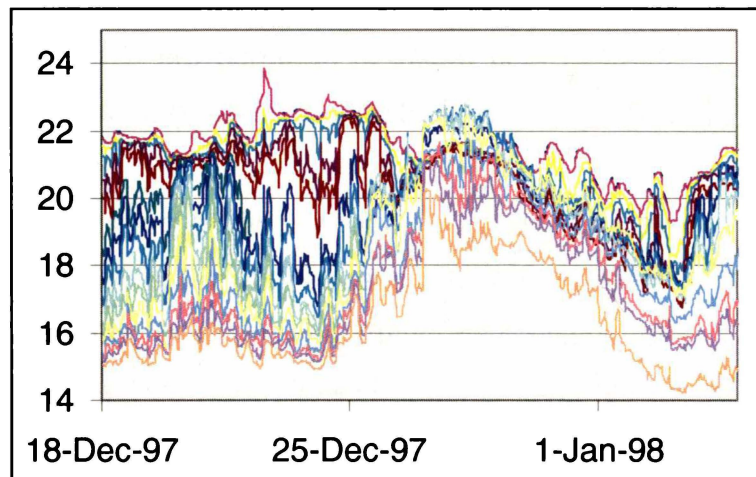
Vertical mixing is important within a stratified water column. Plankton, by definition, has a similar density to the water in which it drifts, but some may be positively buoyant (floatable) or negatively-buoyant (sinkable). The upper layer is typically well mixed so the distribution of plankton is unlikely to be effected by minor differences in buoyancy. But, in the absence of significant vertical mixing, positively buoyant plankton tend to accumulate at the surface, sometimes forming visible blooms, while negatively buoyant plankton sink to the sea floor or to a level where they achieve neutral buoyancy. Because the probability of achieving neutral buoyancy is greatest where vertical density gradients are strongest, plankton typically tend to accumulate near the thermocline.

From ORS data, the coastal waters off Sydney are stratified for most of the year (October-June). That is, warm, low-density water generally sits over cooler bottom waters and inhibits vertical transport (exchanges) through

the water column. The transition between these density layers is often characterised by strong vertical density gradients (pycnocline) which, in our study area, are generally controlled by temperature differences (across the thermocline). Vertical mixing processes in coastal waters may assist in drawing nutrient rich bottom water or sewage effluent from deepwater outfalls to the surface where sunlight is readily available for photosynthesis and phytoplankton growth.

Some vertical mixing may occur across the thermocline because this is typically a zone of current shear. But significant density stratification generally persists unless either a single water mass moves in to swamp the entire water column or a downwelling cell set-up by the prevailing southerly storms in this region, erodes the thermocline. Observations from the moored temperature sensors in Figure 8-9 (off Sydney) demonstrate that stratified waters can be mixed (de-stratified) to depths of at least 52 m over periods of less than 24 hrs under the influence of strong winds and waves.

Figure 8-9: Downwelling favourable southerly winds cause de-stratification of the water column at the ORS during highly stratified summer conditions.



Imbedded in this record are short period internal tidal waves, which travel along the thermocline, and may also contribute to vertical mixing (seen here as movements of 10-20 m) when they shoal and break on the inner shelf. Whilst the de-stratification process may free planktonic material accumulated on the thermocline, the downwelling also typically draws in species from offshore surface waters (typically tropical species associated with the EAC). This type of plankton behaviour was observed during this study by Ajani et al (2001a) and Dela-Cruz et al (2002).

8-2-2 Outfall Effects

High concentrations and loads of nutrients are an intuitive precursor for eutrophication. But many other factors, can limit primary productivity (ANZECC, 2001). These factors include mixing conditions, hydraulic retention time, light, temperature, suspended solids and grazing pressure. The nutrient concentrations and loads from outfalls in the study region, would suggest a considerable potential for algal problems. This is because the receiving water concentrations (in Chapter 3) are generally at or above the concentrations (in surface water) that have been associated with problems elsewhere (ANZECC 1992), and the outfall nutrient loads are high.

The overall finding from the papers in Chapter 6 showed that plankton responded to the episodic intrusions of upwelled water, and that from studies spaced by 20 years a decrease in biomass was recorded. This unexpected decrease was attributed to the strong El Niño of 1997, which masked any expected long term trend.

Companion plankton studies by Dela-Cruz (2002) and Rissik et al, (2002) indicated plankton populations off Sydney were typically aged and showed no shoreward gradient in abundance. Conversely these studies did show higher bio-mass off Port Stephens, and a shoreward gradient of smaller actively dividing cells associated with the back-eddy formation. Conclusions for these blooms were that the Port Stephens region was the remote source for the majority of blooms observed off Sydney during the study period.

But, initial water quality studies (1989-1993) by Coade (1995) in the vicinity of these outfalls did show that there were significant increases in chlorophyll-a subsequent to the commissioning of the deepwater outfalls (Table 8-3). This work represents the longest chlorophyll monitoring undertaken in the study region.

Table 8-3: Chlorophyll-a summary statistics for surface and 20m samples taken during the pre- and post-commissioning phases of the deepwater outfalls off Sydney (1989-1993). From Coade (1995).

Site	Pre-commissioning		Post-commissioning	
	Mean µg/L	Std error	Mean µg/L	Std error
surface/20m samples				
Ph50	0.55/0.49	0.07	1.19/1.38	0.24/0.3
Bondi Ref	0.54/0.42	0.11/0.08	0.95/0.94	0.22/0.14
North Head outfall	0.75/0.74	0.12/0.2	0.95/1.23	0.11/0.35
Bondi outfall	0.81/0.61	0.15/0.08	1.12/1.06	0.18/0.2
Malabar outfall	0.65/0.44	0.08/0.1	1.06/1.05	0.18/0.17

The results in Coade (1995) were considered unfounded as the chlorophyll-a increases occurred at the “impact” and “control” sites and they did not always relate to enhanced levels of the microbacterial indicator, *faecal coliforms*. As a result, the findings in this volume did not follow through to the final assessment report on outfall performance (Pritchard et al, 1995). This omission is questionable for several reasons.

The location of the impact and control sites did not relate to circulation scales associated with plume dispersal. The impacted reference sites were at PH50, and located off Bondi at the 90 m contour in the middle of the three outfalls located at North Head (10 km to the north in 60 m), Bondi (5 km to the west in 60 m) and Malabar (10 km to the south in 80 m). Whilst direct offshore transport from the Bondi outfall to this site is unlikely, reference to plume tracing studies undertaken during this program (Pritchard and Lee, 1996), as summarised in section 3-2, suggest the Malabar outfall could reach this site within 24 hrs during periods of northward flow (~30% of the ORS record) at dilutions of 1:2000. Similarly the PH50 site (~15 km to the south) could be frequently bathed in the dispersed effluent field. Ekman spirals frequently observed in the ORS current record (Lee and Pritchard, 1995), obey Coriolis such that southward flows exhibit a deflection offshore in surface flow and onshore at depth, reversing this pattern for periods of northward flow. Therefore this provides a mechanism to move a northward flowing Malabar plume out to the reference site off Bondi, and a southward plume to PH50. Compounded on the average daily plume excursions of 10-20 km, is

frequent plume surfacing (scales from 20 mins – 2 days) associated storm mixing and current reversals from the passage of internal tides and coastally trapped waves (10-15 day periods). The resultant mixed impact zone rendered many studies that were investigating effects of the Sydney outfalls, unable to resolve impact from control sites.

In fact, a subsequent study on trace metals (which found no differences within the Sydney region) extending along ~1000km of the NSW coast identified average levels in the Sydney studies were several orders above the coherent background concentrations measured outside this region (Apte et al, 1998).

The second concern that arises from the Coade (1995) study, is the rejection of significant chlorophyll-a increases based on poor correlations with *faecal coliform* concentrations. This comparison is doubtful as it is based on incompatible temporal responses in coastal waters. The detection of *Faecal coliforms* typically relates to direct plume impacts (within hours of discharge), and is not considered a useful measure to parallel pathogen pathways (WHO, 2001), that relate to more diffuse effluent impacts. Their presence is often considered qualitative due to the high variation in sample concentrations. Plankton response to nutrients is less rapid with typical doubling rates under optimal conditions of 2-8 days for common diatoms species, and 2 days for *Noctiluca scintillans* (Buskey, 1995). It is therefore suggested here that in consideration of these effects and the statistically significant results from Coade (1995), that the outfalls may be enhancing the baseload of phytoplankton in the Sydney region.

Recently Dela-Cruz (2002) identified a localised phytoplankton response to a surface discharge at Potter Point on the Kurnell Peninsula (south of Sydney). This occurred when highly stratified EAC flows induced back-eddy in the lee of the Kurnell peninsula within Bate Bay. This circulation persisted long enough to effect a locally enhanced population of young dividing *Noctiluca* cells, whilst populations both inshore and offshore of this circulation indicated an aged population of large senescent cells.

The planning, implementation and assessment of chlorophyll monitoring should consider the diurnal to inter-annual scales that are able to affect their abundance, as these studies have shown. Apart from the ad-hoc spring bloom research studies undertaken by CSIRO off Port Hacking (see Chapter 7), the monitoring work by Coade (1995) was the only consistent sampling done to date in the region. This study was not designed as a follow-on monitoring program to Coade (1995)'s, but rather an investigative inter-comparison of the nutrient loads and the associated mechanisms and their effects. So while results from this study indicate the bloom responses are clearly caused by slope-water intrusions, it does not discount the unresolved long-term trend from being ineffectual.

8-2-3 Flood Effects

When extreme flood events override the strong horizontal salinity gradients in the lower estuary of the coastal catchments (making a significant discharge into coastal waters), the highly turbid source that becomes available to the coastal waters can introduce a number of limiting factors for phytoplankton. The floodwaters would initially limit phytoplankton growth by shading, so it is more likely to expect a lagged response from plankton populations. The nutrient ratios in coastal waters can be altered by floodwater discharges. The dissolved phosphorous readily absorbs to colloidal particles in turbid water reducing the immediate bio-available supply, whereas other nutrient species behave relatively conservatively. Nutrient enrichments from floodwaters are mainly in the form of silica and could therefore enhance the silaceous diatom populations.

But from the studies undertaken in Chapter 2 and Chapter 6, no phytoplankton increases responded to the large ~1 in 2 year event of July-August 1998. This contrasts concurrent 12-month studies of fish larvae by Trinski (Pers. comm.) in the region (off Lake Macquarie), where the turbid flush of floodwaters triggered an increase in larval populations. The strongest larval response related to the wet weather events of July-August

1998, whereas abundances were relatively unrelated to phytoplankton patterns measured in this study. Dela-Cruz (2002) also suggests that the dominant coastal water bloom phytoplankton, *Noctiluca scintillans*, like other common species occurs in estuaries possibly acts as seed stock for the blooms in coastal waters. This is represented in Figure 8-10 as an increasing “cell diameter” gradient (estuary to offshore waters), with smaller cells indicating an actively feeding young population. Evidence in other coastal regions also suggest that *Noctiluca scintillans* often blooms after rain events (Paerl, 1997; Dela-Cruz, 2002).

From a review of species in NSW marine and estuarine waters, Ajani et al (2001b) identified ~70% of blooms reported were due to *Noctiluca scintillans* and *Trichodesmium* in coastal waters, with the latter typically sourced from tropical waters of the Coral Sea brought south by the EAC. The majority of the remaining 30% occurred within estuaries. Some 45% of all blooms were due to *Noctiluca* alone, occurring in offshore, coastal and estuarine waters. Perhaps nutrient loads from floodwaters were sufficient enough to flush a dormant plankton species into coastal waters and increase their numbers, but the enhanced grazing pressure from fish larvae may have maintained phytoplankton populations at relatively ambient levels.

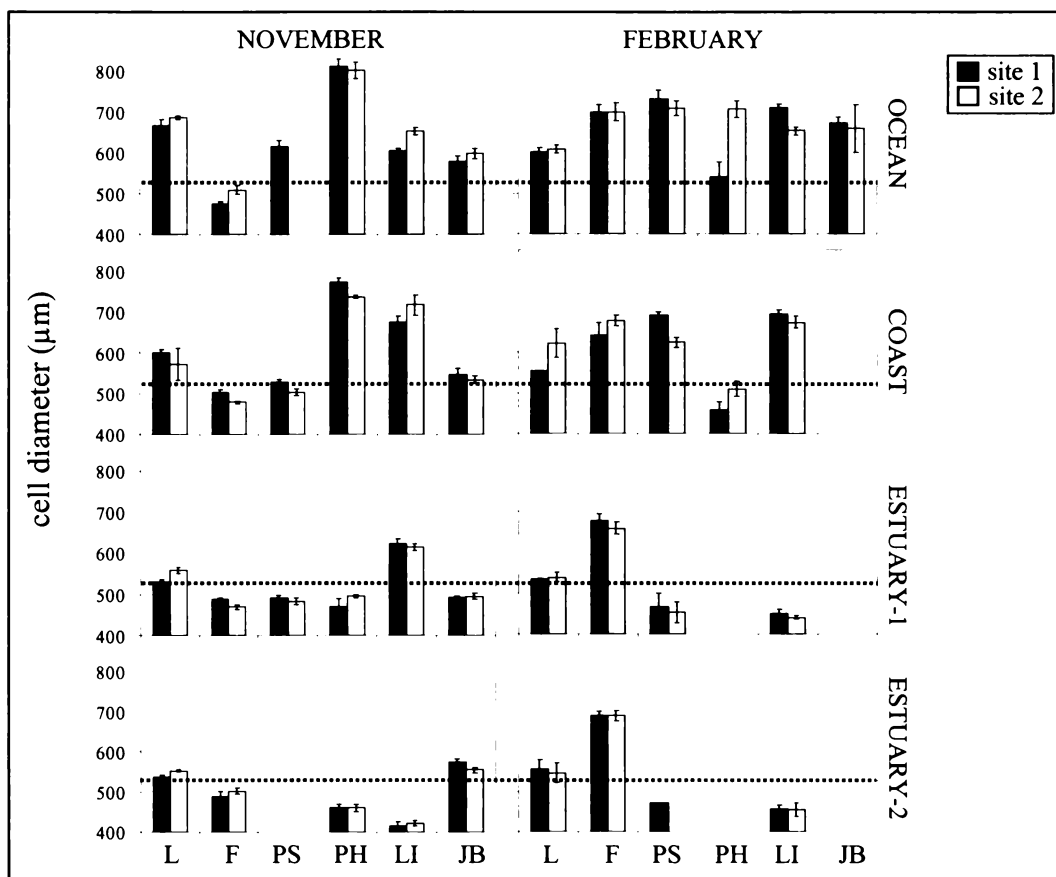


Figure 8-10: Cell diameter representing reproductive status decreasing offshore (from Dela-Cruz, 2002).

8-3 REGIONAL COMPARISONS

This study has highlighted how the dominating oceanic nutrient source influences phytoplankton patterns that can be coherent over a range of spatial and temporal scales. It has also shown that these oceanic intrusions to NSW coastal waters are primarily associated with EAC shelf encroachments and modified by climatic oscillations. Studies by Sprintall et al (1995) indicate that regionally the South Pacific Gyre (which encompasses the western boundary flows of the EAC and the East Auckland current) has both seasonal and inter-annual oscillations. Black et al (1996) indicates that shelf encroachments of the East Auckland Current, off New Zealand's NE coast, is similarly affected by coastal topography as observed in the NSW coastal waters. This section pursues how these interactions and oscillations manifest regionally by re-capping on the observations in NSW shelf waters, and through comparison with conditions experienced on the NE coast of New Zealand.

8-3-1 NSW coastal waters

The temperature moorings utilised throughout the study have indicated both regional and localised conditions effecting NSW coastal waters. These assessments were made primarily on the 50 m moorings located 2-5 km from the coast and indicated well-correlated signals with dominant 8-10 day periods that were coherent for the region south of Port Stephens. The findings in Chapter 4, also indicated that the frequency of intrusion events varied alongshore, associated with major changes in shelf topography. As the 1997-98 mooring array is used in the following section, reference should be made to their locations in Chapter 2.

The four complete 12-month time series from the 100 m moorings at PS01, PH03, PH05 and JB04 spans the alongshore study region, and are utilised here to identify any differences with the 50 m mooring data associated with cross-shelf transfer of oceanic features.

The Fourier analysis of these four moorings for the same 12-month period (Aug'97-1998) are shown in Figure 8-11. Similar to the 50 m alongshore assessment, signals here suggest the conditions off Port Stephens differ

greatly to well correlated moorings to the south, and therefore the effects of coastal topography are shown to extend further offshore.

Distributions of bottom temperature for these alongshore moorings in Figure 8-12, also indicate differing climatology for the Port Stephens region But the 1-2°C southward cooling shifts of the dominant peak at ~15°C, as seen at the 50 m moorings (in Chapter 4), are not present here.

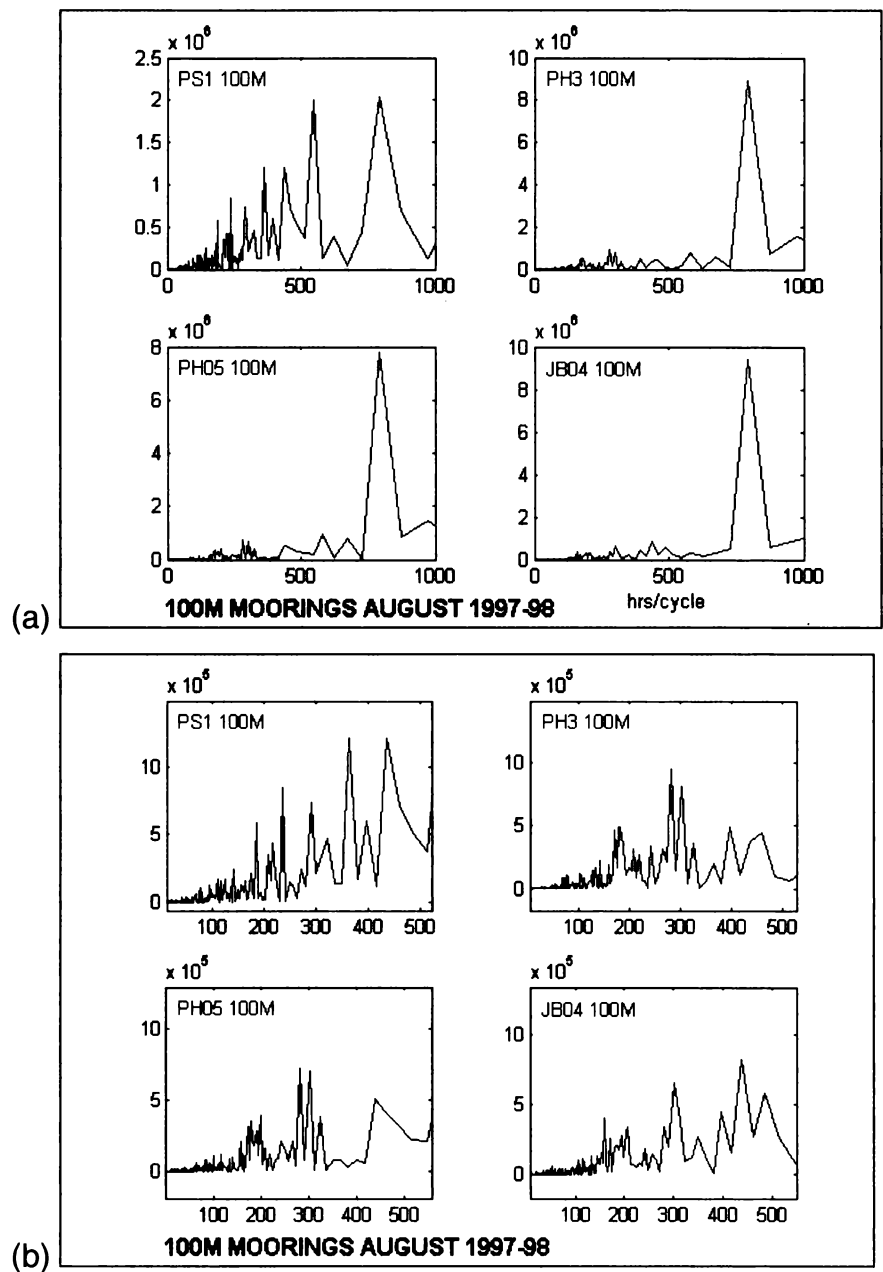
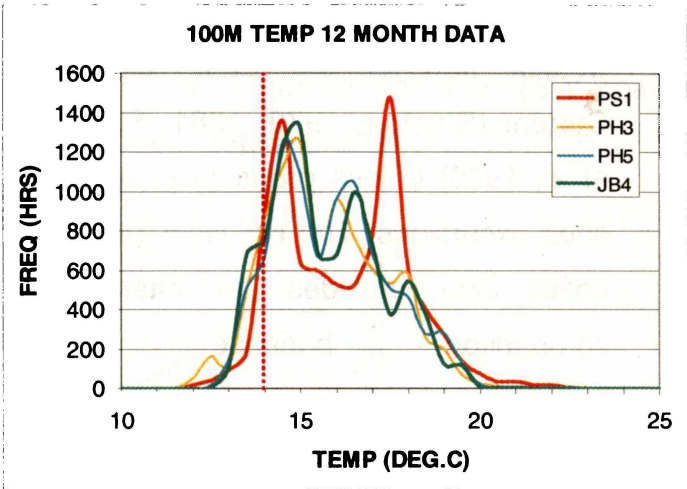


Figure 8-11(a): Data from 12 months of bottom water temperature at 100m Moorings show dominant energy at ~ 33 days (796hrs/cycle) relating to seasonal changes, however for shorter periods in (b), energy peaks occur at 8, 12 and 18 days.

Using a standard 14°C threshold to define intrusions (rather than adjusting for alongshore cooling), indicate respective frequencies for the 100m sites are PS01(14%), PH03(20%), PH05(15%), JB04(18%). The well-correlated bottom water records at the 50m and 100m sites (Table 8-4), show the most marked change between the Port Stephens and Port Hacking regions. While the largest alongshore change in intrusion frequencies were between PS01/PH03 and PH03/PH05, their respective correlations of 0.81 and 0.95, suggest the former is due to differing climatology, whereas the latter is a localised effect of intrusion intensity most likely related to coastal topography.

Figure 8-12: Temperature distributions from 100m sites in the 1997-98 thermistor mooring array, off the NSW coast, Australia.(Note: intrusion event threshold shown as 14°C).



This regional behaviour in the NSW shelf waters is discussed further in section 8-4-2 by analysing along-shore pressure gradients in the context of the long-term patterns.

Table 8-4: Correlations of bottom water thermistors in the 1997-98 mooring array off the NSW coast, Australia.

Mooring	JB04 100m	JB05 50m	PH05 100m	PH04 50m	PH03 100m	PH01 50m	PS01 100m	PS03 50m
JB04 100m	1							
JB05 50m	0.81	1						
PH05 100m	0.89	0.83	1					
PH04 50m	0.81	0.89	0.87	1				
PH03 100m	0.87	0.84	0.95	0.88	1			
PH01 50m	0.74	0.87	0.78	0.90	0.80	1		
PS01 100m	0.79	0.69	0.81	0.80	0.81	0.72	1	
PS03 50m	0.75	0.75	0.79	0.85	0.79	0.81	0.87	1

8-3-2 NE New Zealand coastal waters

To assist in the understanding behind conditions promoting algal blooms in NSW coastal waters, the transect sampling studies (see section 2-3-2) were expanded to the NE coast off New Zealand (Figure 8-13). With reference to the discussion in chapter one, both locations represent temperate shelf waters that interact with the geostrophic flow of tropical water associated with the South Pacific Gyre. But the NE New Zealand shelf presents a more insulated shelf system to this flow due to island barriers and a broadening width. Although linked by the Tasman Front to the East Australian Current, the ~50% weaker flow of the East Auckland Current (Stanton, 1979, 1981; Stanton et al, 1996) is less prone to prolonged shelf excursions. The NE New Zealand coast also provides an interesting comparison because here anthropogenic inputs are low yet bloom occurrence is frequent (see Chapter 1 literature review).

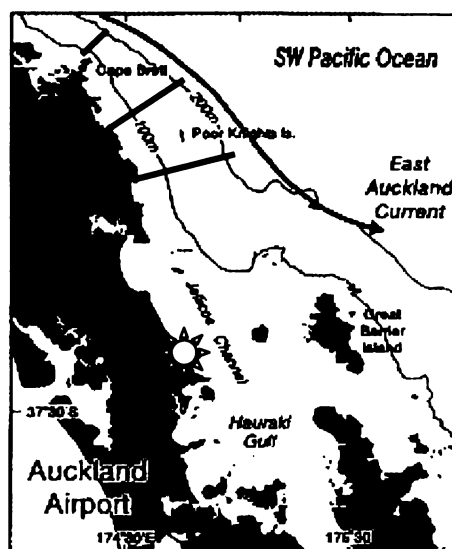


Figure 8-13: Locality diagram showing region of transect work off Cape Brett (A), Rimariki Is (B), and Cape Rodney (C) on New Zealand's NE shelf, and the coastal monitoring station, Leigh (♦).

Results from the 1993-97 sampling transects are supplemented here with 1994-2001 monitoring data from the Leigh Laboratories coastal station off Goat Island (shown in Figure 8-13). This invaluable long-term sampling record of nutrient and chlorophyll species, has been undertaken on a ~weekly basis by Brian Dobson to capture phytoplankton patterns in this coastal region. The development of this monitoring program by the Auckland University's field station was inspired by the extensive blooms during 1992/93 which severely disrupted mariculture operations in the Hauraki Gulf. Studies since have shown the southward flowing East Auckland Current often interacts with shelf topography forming gyres (Black et al, 1996) and can combine with periods of low wind stress to

transport subtropical water associated with oceanic dinoflagellates onto the shelf (Sharples, 1996).

Whilst the NSW study has shown the importance of shelf topography interactions with the EAC to drive slope-water intrusions onshore on the east Australian coast, Zeldis et al (2000) cites seasonal patterns of NW and SE winds corresponding respectively to upwelling and downwelling, dominated conditions on New Zealand's NE continental shelf.

Observations by Dobson (Pers. comm.) from Leigh Laboratories (Figure 8-13), noted frequent blooms of the dinoflagellate *Noctiluca scintillans*, during 1993-2001 spring-summer seasons. This site shows that while temperature patterns are coherent and in-phase with the NSW coastal station, PH50 (surface waters), nutrient patterns differ (Figure 8-14).

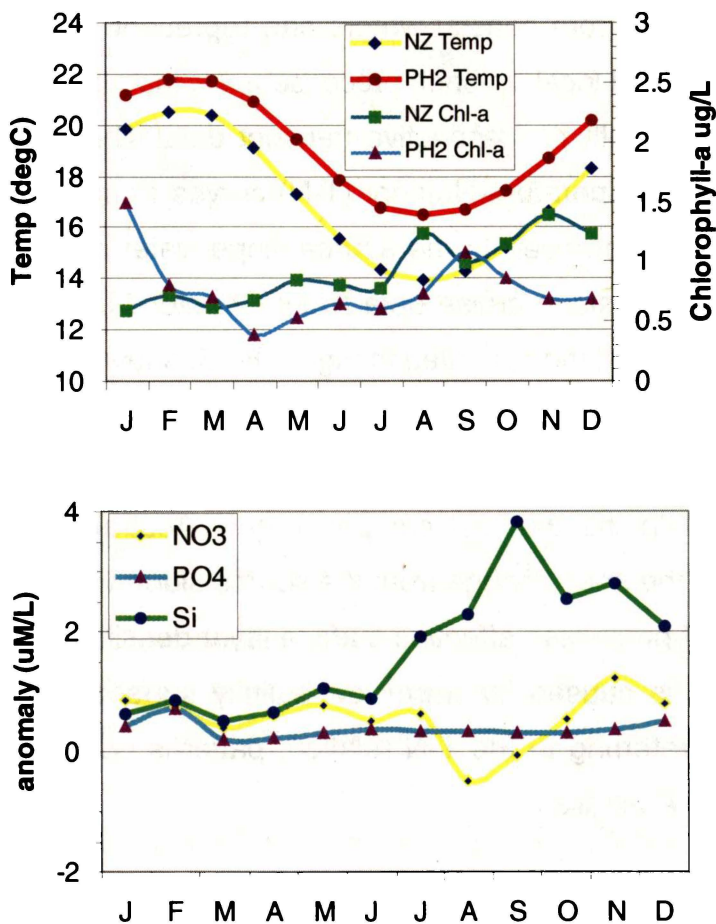


Figure 8-14: Surface monitoring off Leigh Laboratories, NE New Zealand and PH50, Australia show average annual cycles for temperature(1) and chlorophyll-a(2) and anomalies for Nitrate & Phosphate (3) and Silica(4).

1. Leigh (1967-2001);PH50 (1942-1998)
2. Leigh (1994-2001);PH50(1978-79,1997-98)
3. Leigh (1994-2001);PH50(1967-1998)
4. Leigh (1997-2001);PH50(1971-1998)

These results suggest the 1-2°C cooler waters off New Zealand exhibit higher nutrient levels and have an overall larger biomass than coastal Australian waters. The phytoplankton response in New Zealand reacts to winter overturning with peak activity in late spring corresponding to surface water nutrient peaks. This response typically follows regional wind stress patterns, where upwelling favourable north-westerly wind stress is strongest during winter and spring (Zeldis et al, 2000). As downwelling favourable south-easterly stress builds during mid-late summer, biomass decreases. Whilst the spring bloom in Australia has similarities to New Zealand, from this study the late summer peak related to maxima at depth and was associated with localised EAC dynamics.

As monitoring results from coastal waters can represent an amalgum of oceanic influences and local on-shelf processes, it is instructive to develop comparisons further with the respective transect data. The Temperature-Salinity (T-S) and Temperature-Nutrient (T-N) curves from the respective coastal waters are referenced to the source slope-water curves obtained from the CSIRO shelf-slope cruise data (from Chapter 5). The three NZ transect T-S and T-N relations plotted in Figure 8-15, show that T-S curves are maintained across the Tasman.

As experienced with the transect comparisons in Australia, the warmer surface layers on the shelf diverge from the source slope-water isopycnals indicating on-shelf processes affecting surface layer densities. In particular for Australia, this is caused by warm low salinity surface waters of the EAC. But when referring to the T-N relation, patterns do differ from the shelf transects off Australia.

All transects show an offset (similar to the coastal monitoring stations) due to the cooler water present, and nutrient ranges (NO_x-N 0-180 µg/L; FRP 0-25 µg/L) that are in general agreement with the Australian conditions (in Chapter 5). The T-N distributions for phosphorous increasingly diverge from the relatively linear source water reference with distance downstream

from the Cape Brett transect such that the relation becomes strongly exponential. Considering the differences between discharges from the Hawkesbury and Hunter catchments experienced in Chapter 3 studies, it is likely that the terrestrial effect of predominantly basaltic soils in NE New Zealand are contributing to the enhancement of phosphate in cooler bottom waters.

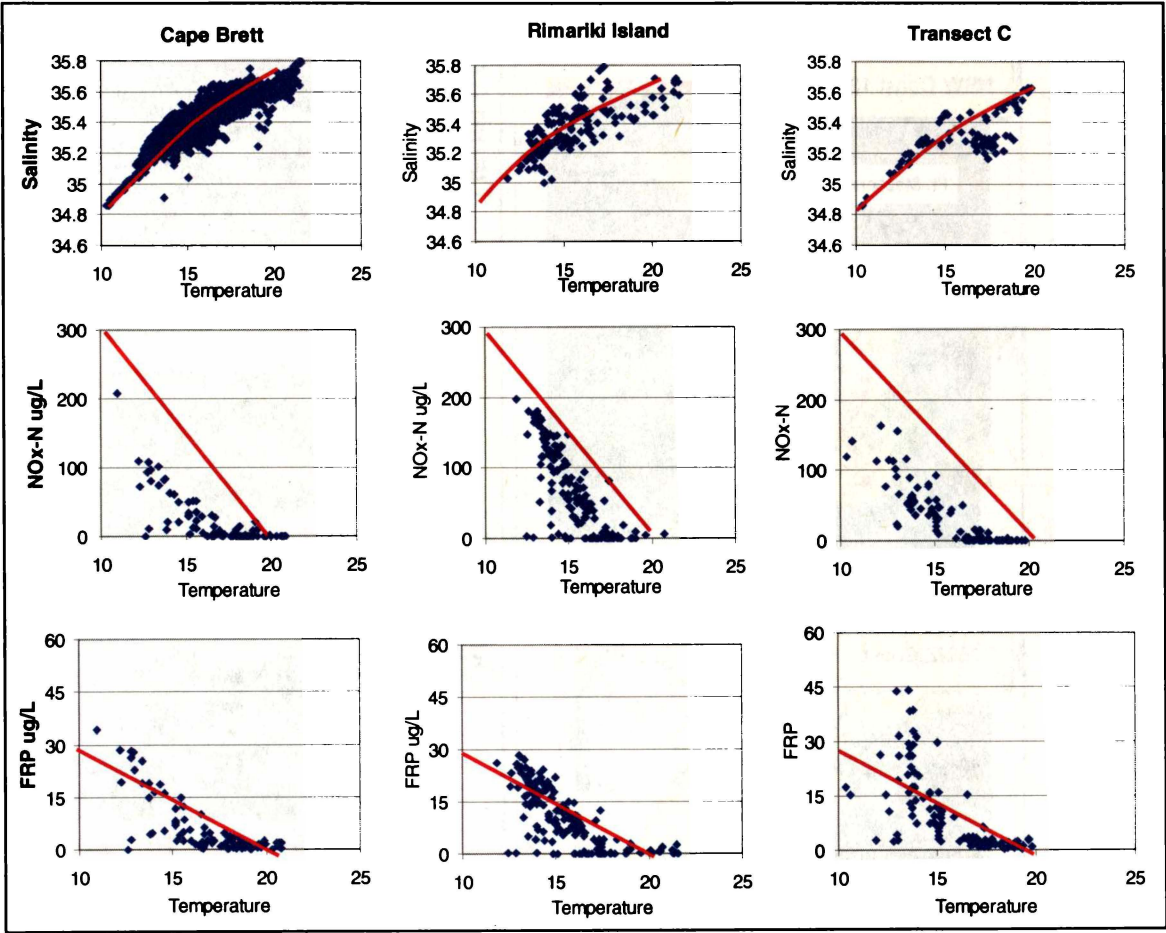


Figure 8-15: Temperature -Salinity and Temperature-Nutrient relations from NZ transect lines (A,B,C) with respect to the slope-water reference curves (as red dotted lines are relationships derived from source slope-water off eastern Australia).

The upwelling scenario sampled along the Rimariki Is. transect, on the 16 January 1996 (Figure 8-16), is suggestive of a coastal upwelling set-up similar to the observations of EAC shelf encroachments off Australia in January 1997 (Chapter 5).

The NOAA SST image for the 16 January 1996 in Figure 8-17, that companions the transect data, indicates geostrophic flow along the NE New Zealand coast interacting with local topography, and in particular causing localised upwelling in the lee of Cape Brett.

Figure 8-16: Line B transect showing upwelling on 16 January 1996.

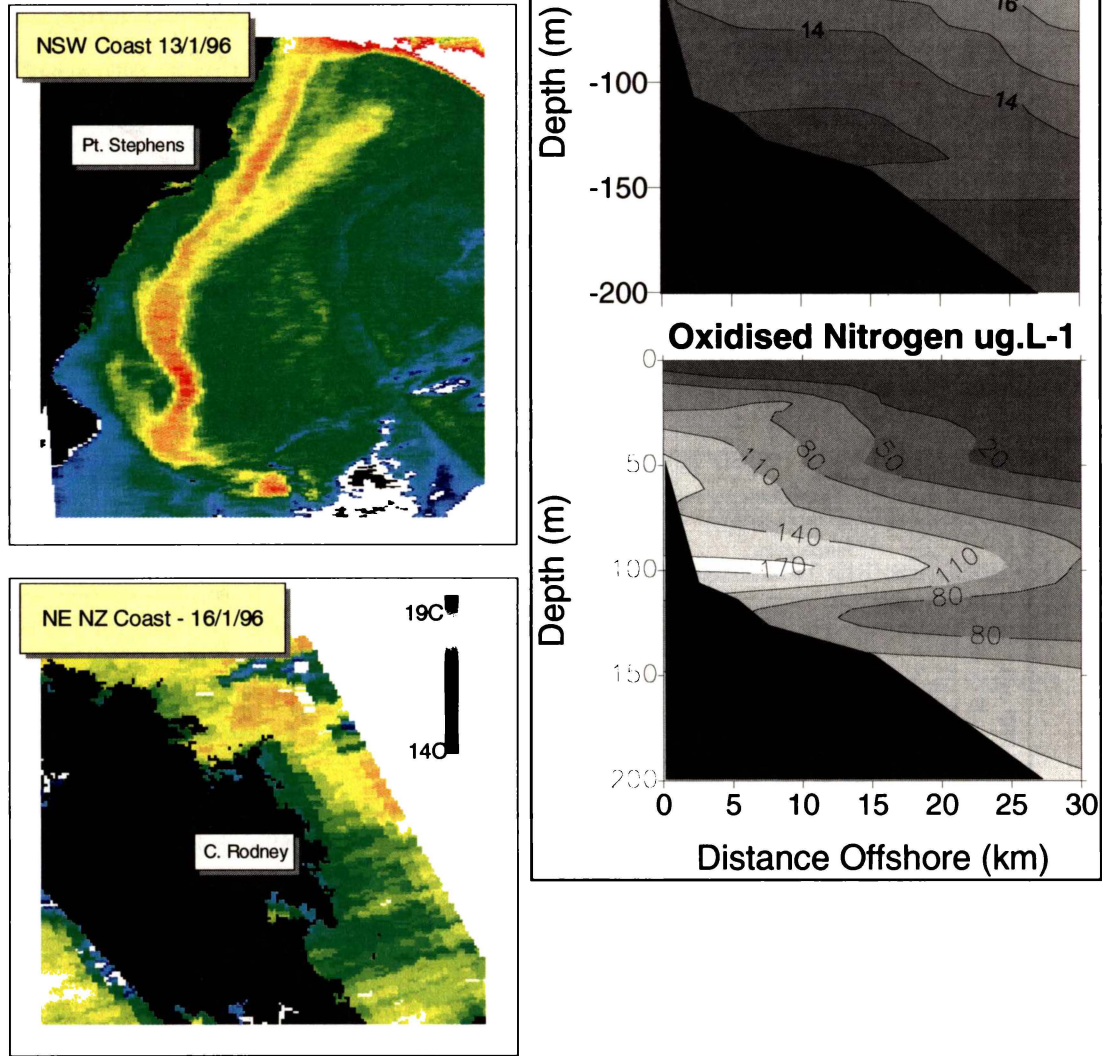


Figure 8-17: (a) SST image for 13 January 1996, shows small scale turbulence of EAC flows associated with coastal topography off the NSW coast, and (b) SST image for 16 January 1996 around NZ, indicates upwelling in the lee of Cape Brett, and extending south past Cape Rodney.

On long-term scales oceanographic similarities are also apparent between these two shelf systems. The Southern Oscillation Index (SOI) has been attributed to fluctuations in sea surface temperatures off Leigh Laboratories. Monthly averages of daily samples shown in Figure 8-18 show a well-correlated signal of cooler (-SOI) and warmer (+SOI) episodes. As the findings in Chapter 7 showed, anomalous 1-2°C warming is associated with El Niño (-SOI) period, so it is not surprising that the inverse of the New Zealand signal is resolved in surface waters at the ORS.

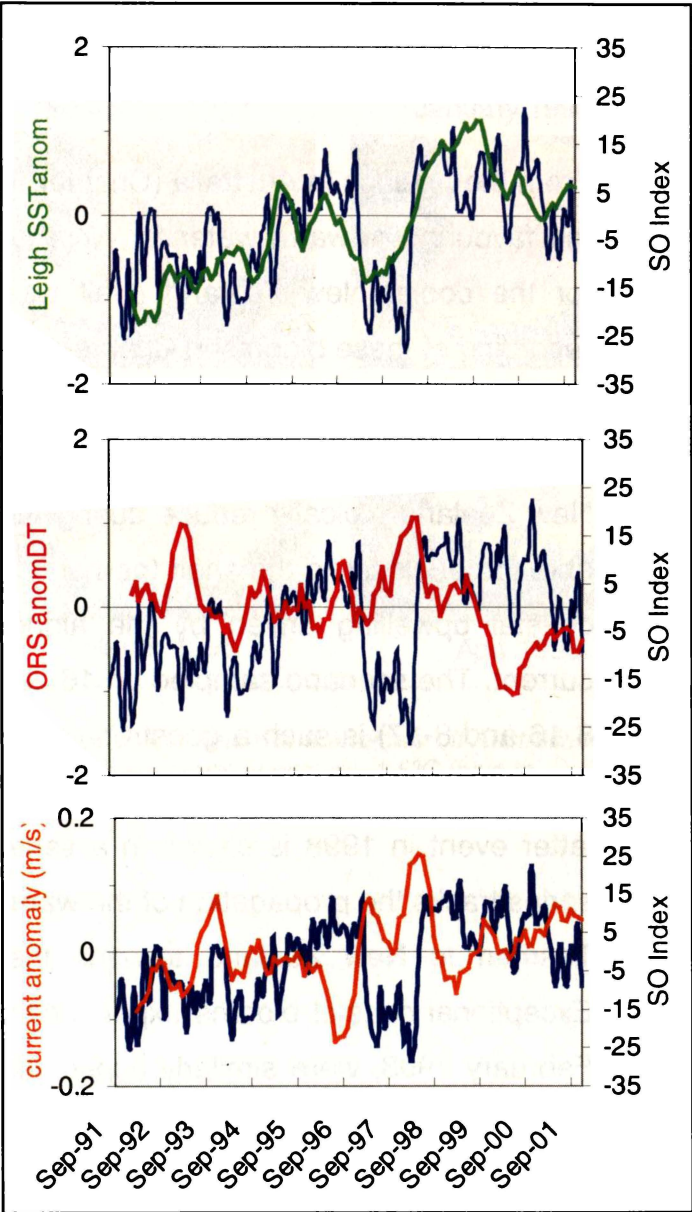
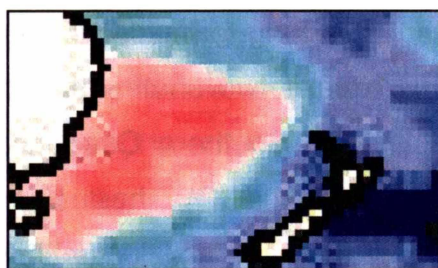


Figure 8-18: 1991-2001 Monthly means of SST anomalies at Leigh in NE New Zealand and temperature stratification (DT) and alongshore current at the ORS (off Sydney) correlate well to the SOI (in blue).

Figure 8-18 shows this manifestation as temperature structure and associated alongshore flow at the ORS, where higher stratification (and flow) conditions persist during –SOI episodes. This inverse relation with the SOI is shown in the cross-Tasman SST anomaly for the strong 1982 El Niño in Figure 8-19. As many plankton species (e.g. *Trichodesmium*) in this region are sensitive to optimal temperatures for growth, these anomalous periods would be a limiting factor in their abundance.

Figure 8-19: SST anomaly image shown for 1982 El Niño (September'82), indicates warm anomaly off eastern Australia and a cool anomaly off NZ (from Allen et al, 1997).



From the findings in Australia (Chapter 6), the favouring of warm water for *Noctillua scintillans* is particularly crucial for the cooler New Zealand shelf waters. With reference to previous recording of these blooms in Chapter 1 (Table1-1) and subsequent reports at Leigh (Dobson, Pers. Comm.), their occurrence coincided with the onset of La Niñas of 1995/96 and 1998/99. As wind driven upwellings off NE New Zealand typically reduce during the La Niña phase, the EAC-NZ is able to get closer to the shelf (perhaps assisted by SE winds) allowing for coastal upwelling driven by the alongshore pressure gradient of the current. The scenario sampled on 16 January 1996 by this study (Figures 8-16 and 8-17) is such a geostrophically driven upwelling event, resulting in unusual mid-late summer blooms in the region. A closer look into the latter event in 1998 is shown in a series of images in Figure 8-20. The series tracks the propagation of the warm anomaly off Australia across the Tasman to New Zealand towards the end of the 1997/98 El Niño. Exceptional coastal blooms experienced in Australian waters in January-February 1998, were similarly experienced in March-April along the New Zealand's NE coast and species were attributable to this warm oceanic source (Chang et al, 1998).

The narrow continental margin of the NSW coast is well flushed by the adjacent EAC oceanic flow, so it is most likely only in coastal areas buffered from the ocean's geostrophic gradient by physical retention (embayments, back-eddies and coastal boundary layers) that plankton blooms are able to manifest. This insulation is more pronounced on the broadening shelf off New Zealand's NE coast, resulting in a system more predisposed to wind driven intrusions resulting in plankton blooms. While EAC is more influential to shelf processes manifested in the seasonal upwellings of mid-late summer, this study has also shown that coastal upwellings driven by the weaker EAC-NZ can introduce slope-waters to

the Hauraki Gulf from upstream sources (eg Cape Brett) where the shelf is narrow enough for significant oceanic interactions to occur.

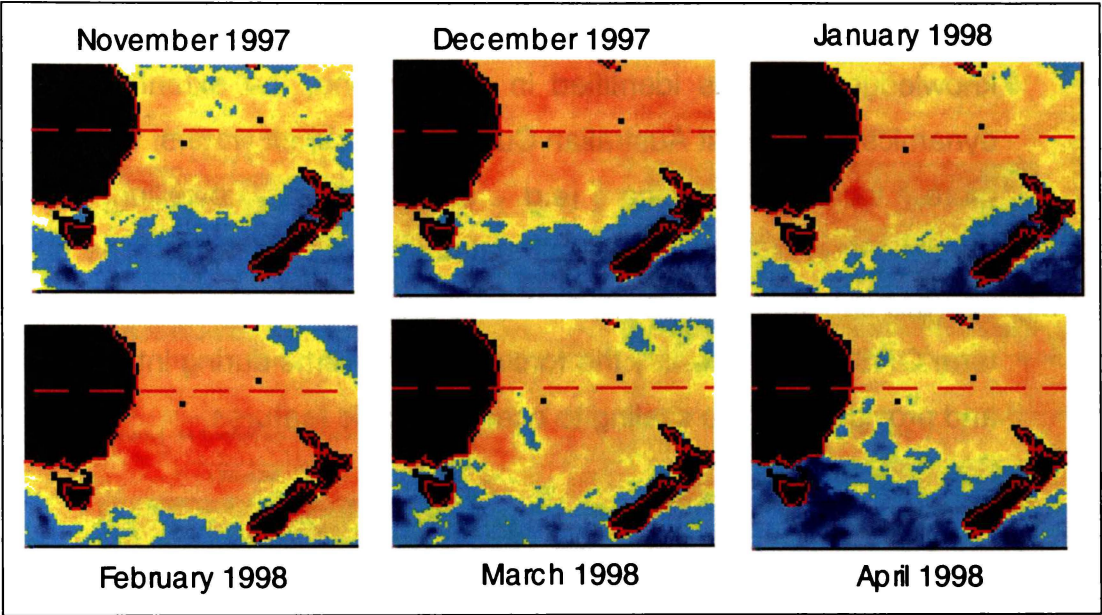


Figure 8-20: At the end of the of the 1997 El Niño the warm anomaly off Australia moves across the Tasman to New Zealand (anomaly range shown as -1.5°C (blue to +1.5°C(red)).

8-4 LONG TERM PATTERNS

The forth objective of this study is to indicate how representative the study was in the context of long-term climate variation. With reference to the knowledge shortfalls identified in chapter one, the extent to which the dynamics of the East Australian Current affect shelf waters, with respect to more localised forcing (e.g. wind-induced upwelling), requires quantification to form an overall statement which partitions the dynamics that are causing the upwelled intrusions. The following section uses long-term ORS data to identify the forcing mechanisms during intrusion events, and provides relative scaling to oceanographic features.

8-4-1 Upwelling Signals (ORS 1990-2000)

Previous studies by McClean-Padman and Padman (1991) had identified over twenty upwellings off the Sydney coast during the period 1974 - 1978. They utilised wind stress data and T250 maps (generated from routine XBT surveys) to partition upwelling scenarios according to upwelling favourable winds (40%) and EAC shelf forcing (35%). These studies neglected topographic effects and failed to identify intrusions from remote upwellings. This thesis has shown these to be significant contributors of oceanic nutrients enriching the euphotic zone.

To investigate long-term upwelling patterns, the 12-year record at the ORS (Dec 1990-Dec 2001) utilised the cool temperature signal in bottom waters to identify major intrusions. Papers in Chapter 4 and 5 identified that the intrusions were related to strong southward flow and well stratified conditions, and less so to favourable wind forcing. Temperature structure, alongshore winds, and surface (15 m) alongshore currents are plotted in Figure 8-21 and 8-22 for representative spring and summer bloom periods. For each of the seven scenarios it is possible to infer the key forcing components by assessing temperature structure, current and wind patterns. Southward wind and current components provide favourable conditions for intrusions, with surface cooling suggesting the mechanism is occurring locally. A moderate southward flow with surface warming is

indicative of a more remote upwelled source, as the intrusion is entrained downstream by the warm EAC. From the examples in Figures 8-22 and 8-23, a majority of the events have combinations of components present, as described next.

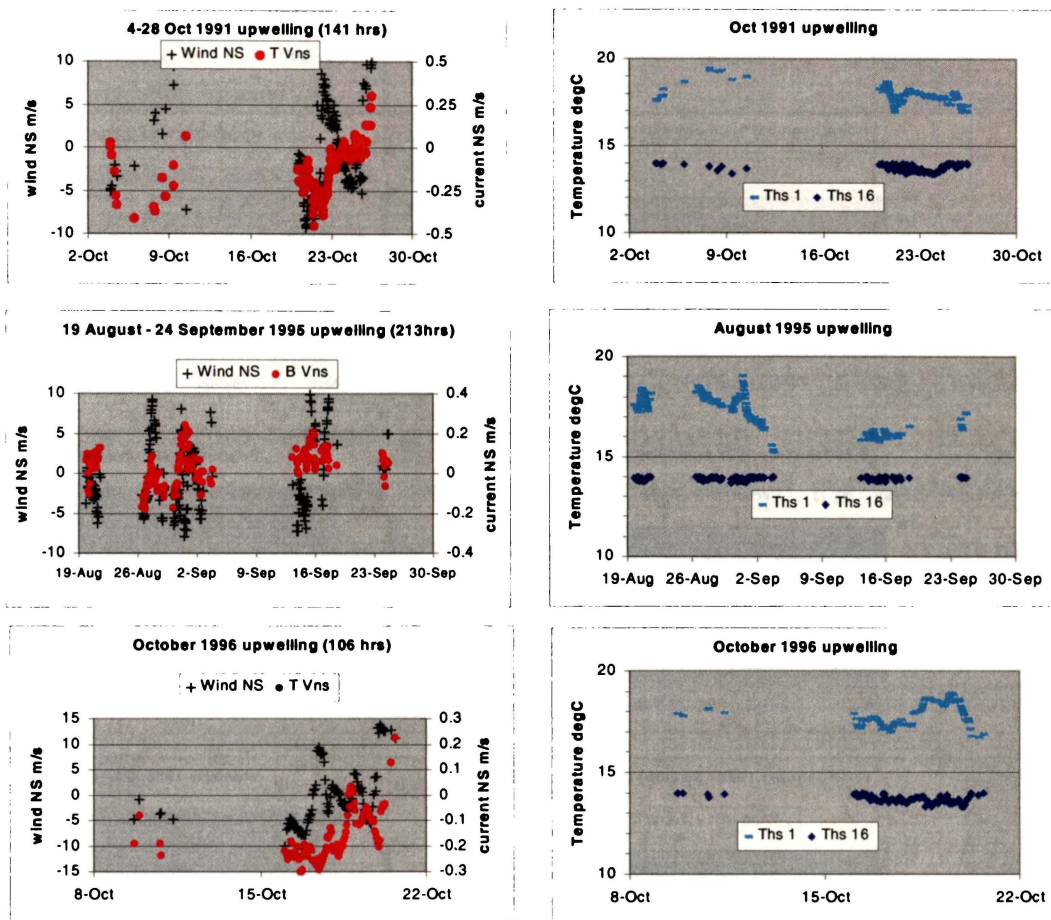


Figure 8-21: Intrusion events at the ORS during the spring bloom period.

The data were investigated further using these key measures of forcing to determine their relative weights. Using a $\leq 14.5^{\circ}\text{C}$ threshold on the ORS's 52 m thermistor, corresponding to ~5% subset of the full record, parameters were considered for both exclusive and inclusive events. Results shown in Table 8-5 show prevailing EAC southward forcing as the key parameter with an occurrence of 90%. Combinant wind and current forcing was also a relatively frequent cause, however upwelling favourable wind in isolation of southward EAC was a rare occurrence. Remote forcing indicated as a warm surface layer in combination with a prevailing southward current was occurring ~twice as often as locally-driven intrusions.

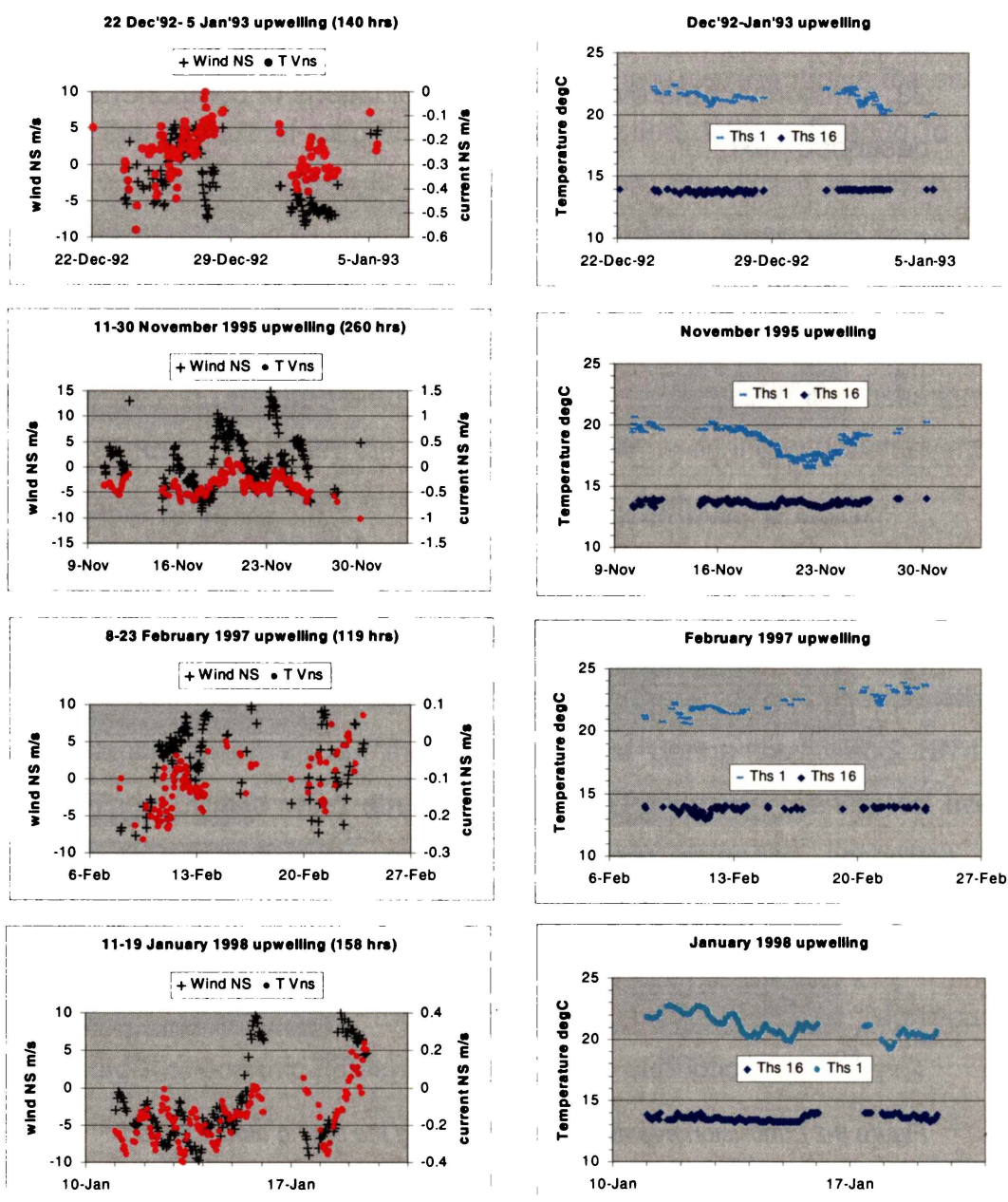


Figure 8-22: Intrusion events at the ORS during summer bloom period.

Utilising an ~8-year record ($n=2^{16} \equiv 65536$ hours) from the ORS (from November 1990 – December 1998), Fast Fourier Transforms were performed on these four parameters (alongshore current and wind components and top and bottom temperature), to isolate the dominant length scales over the long-term period in the coastal waters.

Table 8-5: Intrusion events sensed at the ORS are partitioned for exclusive and inclusive conditions of the key forcing indicators T_{NS} (alongshore current), W_{NS} (alongshore wind) and t_1 (surface temperature).

Condition	N (hrs)	Occurrence
$T_{NS} < 0$ (Alongshore current)	2690	90%
$W_{NS} < 0$ (Alongshore Wind)	1609	54%
$T_{NS} < 0 \ \& \ W_{NS} < 0$	1521	51%
$T_{NS} > 0 \ \& \ W_{NS} < 0$	88	3%
$T_{NS} < 0 \ \& \ W_{NS} > 0$	1081	36%
$T_{NS} < 0 \ \& \ t_1 > 19$	1303	44%
$T_{NS} < 0 \ \& \ t_1 < 18$	831	28%

Figure 8-23 shows the spectra for the $n/2$ (4-year) period, indicating expected annual cycles dominated temperature structure, but also showing that wind energy dominates as expected in the weather-band period (8 days), and alongshore flow has dominant energy in an inter-annual signal.

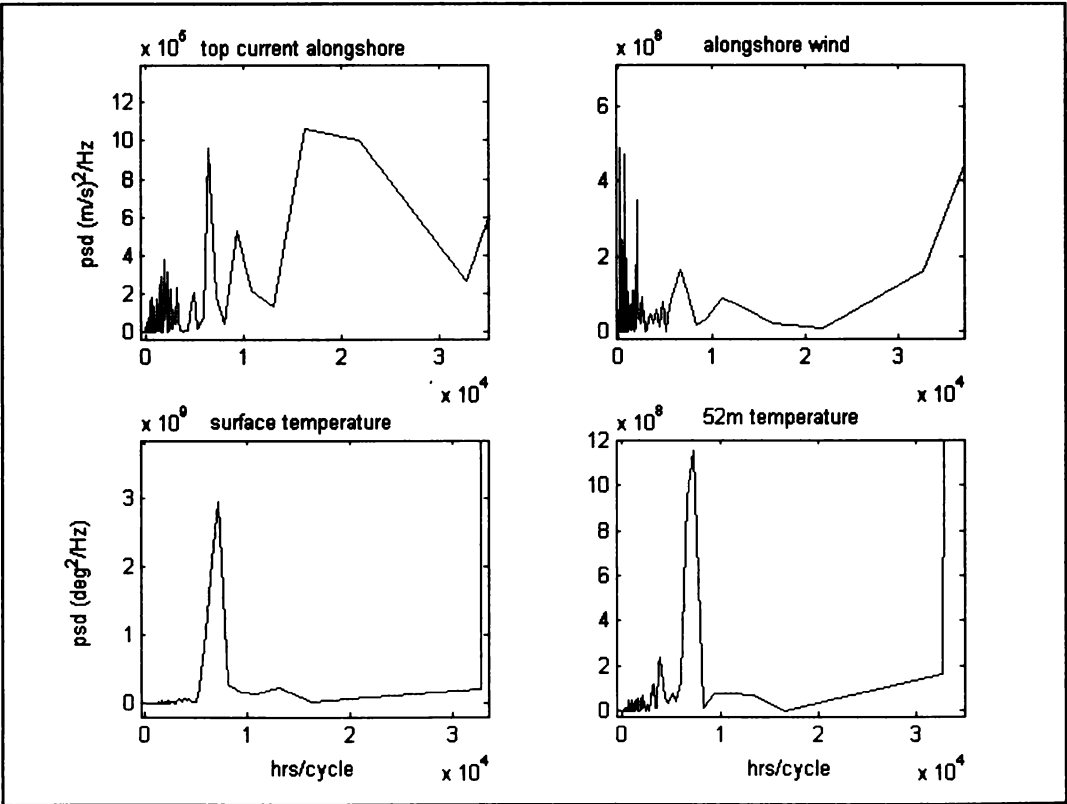


Figure 8-23: Power spectra for alongshore current and wind components and temperature structure for $n=2^{16}$ hours (1990-98) at the ORS.

The dominant 2-year signal in the alongshore current is matched by the ENSO signal during this period (see Figure 8-18) with more dynamic flow conditions at the start and demise of an El Niño. As this inter-annual climatic signal is the topic of interest in this section, a look at long-term records of the alongshore pressure gradients is instructive to identify whether this local coastal feature is expressed regionally.

8-4-2 Alongshore Gradients

Coastal sea level data from Port Stephens and Sydney in Figure 2-11 (data as used for the simulated temperature structure referenced in Chapter 2) are employed here to investigate the alongshore pressure gradient signal associated with geostrophic forcing of the EAC in the study region.

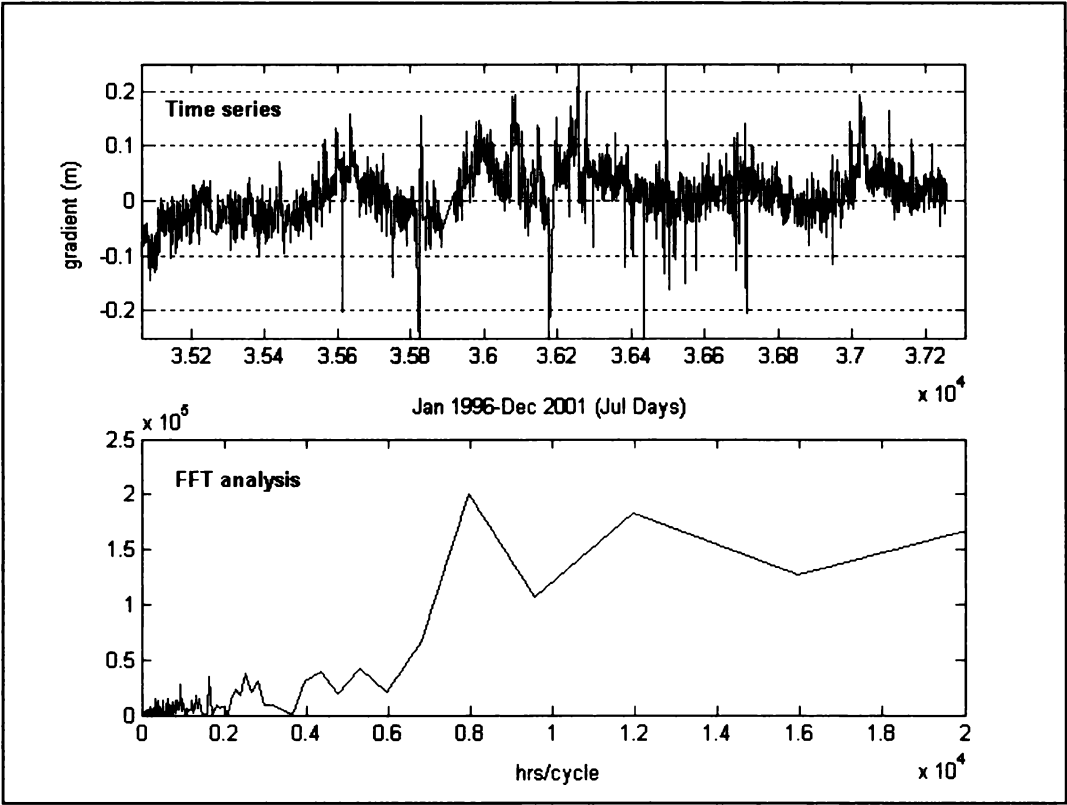
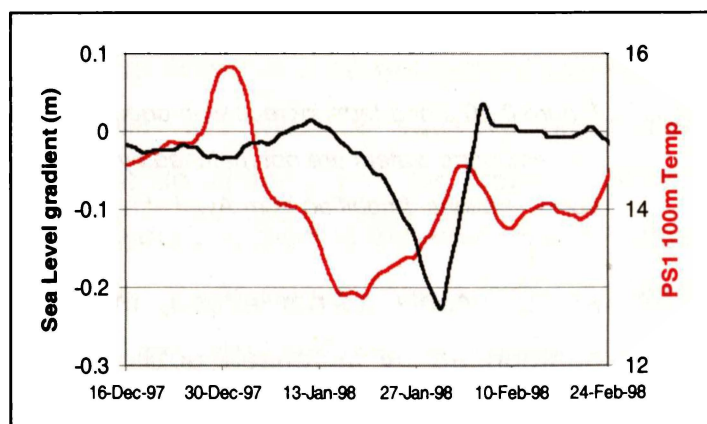


Figure 8-24: Sea Level Gradient between Port Stephens and Sydney 1996-2001 shown as a time series and power spectra.

Signals were filtered at 25 hrs to remove diurnal and semi-diurnal signals (tidal, sea breeze, solar radiation) to isolate low frequency signals. Figure 8-24 displays a prevailing seasonal signal (~0.2 m oscillations) in the

gradient occurring at both sites imbedded with shorter monthly and weekly periods (0.05 m oscillations), for a six-year period (1 January 1996 - 31 December 2001). The seasonal shift between a high gradient during winter and low in summer reflects the seasonal impact of the EAC off Sydney. This relates to distinct differences of temperature distribution observed in the thermistor array (Chapter 4 and Figure 8-11) between the Port Stephens locality and the region southward to Jervis Bay. The bi-annual signal corresponding to the ENSO fluctuations during this period has a similar energy to the seasonal signal, matching the analysis seen in the along-shore current component off Sydney (in Figure 8-23). Of interest to earlier discussion on scaling, are the short-period anomalies that can be greater than the dominant seasonal amplitudes. Strong negative anomalies are seen during summer periods, whereas positive signals occur during winter. The summer signals relate to cooler water (lower level) off Port Stephens that results from topographically induced turbulence of the EAC. The strong back-eddy observed during this study in January 1998 provides a good example of this feature in the gradient signal. This anomaly seen at ~35800 Julian days in Figure 8-24, is shown in detail in Figure 8-25, with a bottom water signal from the PS1 100 m temperature mooring. The frequency of these events observed in the pressure gradient signal (in Figure 8-24) suggest these anomalies may provide a simple means to monitor back-eddy formations (and their relative intensity), which this study has shown can lead to extensive algal blooms in the region.

Figure 8-25: The Port Stephens – Sydney coastal sea level gradient, indicates a strong negative signal during the back-eddy formation off Port Stephens in January 1998, corresponding with local reductions in bottom water temperature at the 100m mooring PS1.



8-4-3 Phytoplankton Overview

From the longest period of routine chlorophyll-a sampling in coastal waters (1989-1993, from Coade, 1995) this study has indicated concentrations had significantly increased after the deepwater outfalls were commissioned. Since the 1978 12-month plankton study, discharge volumes had increased by ~10%, yet in comparison to the 1997 study the nutrient levels (and bio-mass) were higher during 1978/79. Since the commissioning of deepwater sewage discharge off Sydney, the presence of the eutrophic indicator species *Noctiluca scintillans* has occurred in unprecedented proportions during two summer seasons (1992/93 and 1997/98), although findings in Chapter 7 suggest these anomalous blooms are related to conditions during El Niño episodes.

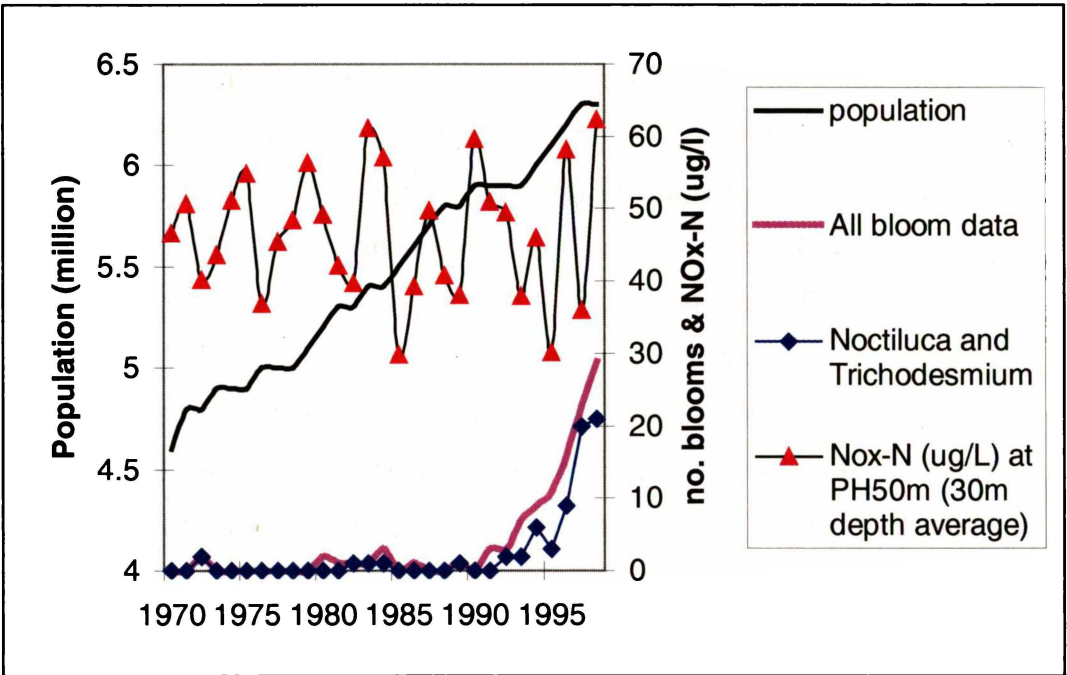


Figure 8-26: Long-term increases in population and bloom observations in NSW marine and estuarine waters are not matched by annual averages of oxidised nitrogen concentrations. (modified from Ajani et al, 2001b).

As commonly acknowledged, the increase in bloom reports may be confounded by increased public and scientific awareness (Hallegraeff, 1993). Figure 8-26 shows how population may also bias increases in bloom observations. While the dominant ENSO oscillations (reference to Figure 8-18) in ambient NOx-N levels are apparent in bloom observations,

they are overwhelmed by a rapid increase in reports during the 1990's. This bias was enhanced by the NSW EPA's ocean nutrient and phytoplankton project which solicited and facilitated reporting and recording of blooms from 1995 to 1998 (between Port Stephens and Jervis Bay) and inevitably contributed to the high reporting frequencies at these locations and during these years. For example, the extensive *Noctiluca scintillans* blooms observed off Sydney and Port Kembla during January-February 1993 were recorded as a single bloom event while during January-February 1997, 11 individual reports of *Noctiluca scintillans* blooms were recorded. Water discolouration is also an important factor in the reporting of algal proliferations. Green algal blooms blend somewhat with the naturally changing spectra of coastal waters, and therefore are likely to go unreported. The more prominent bloom colours such as yellow, brown, red or milky (Hallegraeff 1992) are more 'visible' discolourations, and are therefore more likely to be noticed and recorded. In fact, if the highly visible *Noctiluca* and *Trichodesmium* blooms are removed altogether from the bloom reports, the remaining 30% of reports are predominantly estuarine blooms.

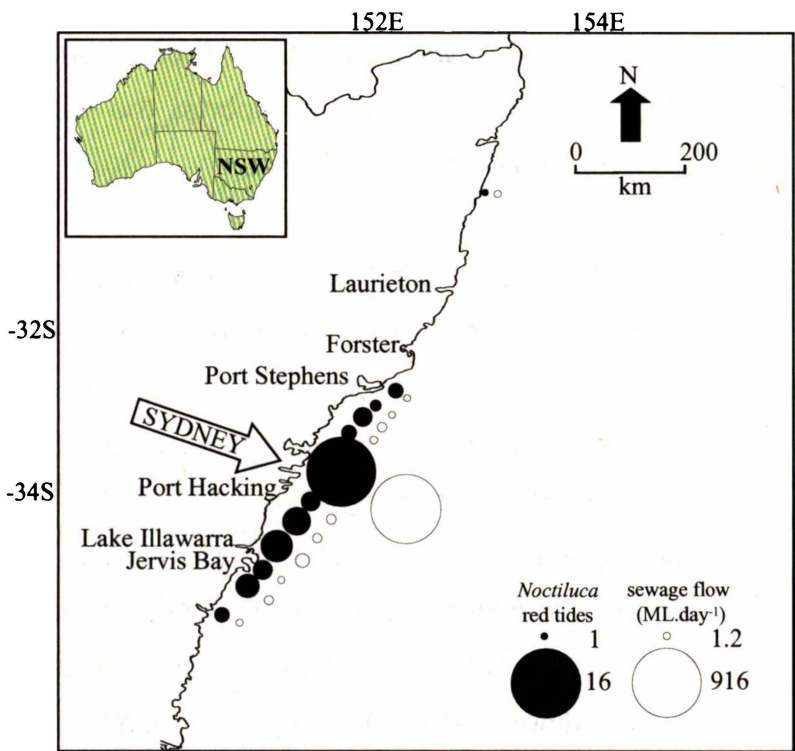
From study reviews in Chapter 3, numerous laboratory and coastal marine mesocosm experiments have attempted to address the effects of nutrient speciation on plankton populations to trace effects of increased anthropogenic input. For example, long-term changes in the N:P ratios from Tolo Harbour, Hong Kong (20:1 to 11:1 in 8 years), were shown to be accompanied by increases in blooms of non-siliceous phytoplankton groups (Hodgkiss and Ho 1997), resulting in a corresponding change in the phytoplankton community, with the red tide causative organisms (mainly dinoflagellates) taking over dominance from the diatoms. Whilst N:P ratios change seasonally off Sydney, providing the most optimal ratios during spring and summer (Chapter 3), the annual means from long term records (Chapter 6) did not register such changes, with stable annual means of ~8:1 from over 30 years of monitoring. In agreement with Sommer (1994), the study here also resolved species preference of

optimal nutrient ratios and temperature conditions with diatom–dinoflagellate (*Thalassiosira* – *Noctiluca scintillans*) bloom successions.

As the predominant load of nutrients from outfalls is in the form of ammonia, rather than nitrate, this may provide the potential to shift phytoplankton species composition in conjunction with enhancing N:P ratios. Certainly when considering the number of observed red tides in the region, and their apparent increase in frequency over the last thirty years (Figure 8-27) it appears that blooms are well correlated to outfall loads. The red tides however, mark the end of population growth since the cells are either dead or dying, and are therefore the end result of a long series of biological and physical processes that may have occurred in temporally or spatially distant water masses (Uhlir and Sahling, 1990). So the spatial distribution patterns of *Noctiluca* red tides associated with this time lag would therefore be a product of the large-scale advective processes.

Figure 8-27:
Observed red tides
and associated
sewage discharges
on the NSW coast
(from Dela-Cruz et
al, 2002).

The distribution
of *Noctiluca*



blooms in Figure 8-27 also reflects the region where the EAC eddy field retains a Tasman-Coral Sea dynamic at the shelf break for periods of weeks. In contrast, the EAC jet stream, which dominates coastal regions further north, has associated short-term blooms of tropical species such as *Trichodesmium*.

This summary of study findings and associated long-term observations, highlights the confusion of any perceivable long-term trend caused by increases in anthropogenic discharges to coastal waters with inter-annual fluctuations. Figure 8-28 simplifies these signals (from findings in Chapter 7) to compare their relative strengths to the seasonal oscillation. With the inter-annual signal able to account or modify the seasonal signal by ~15%, suggested long-term trends of <1% over 20 years can be easily swamped and are often at the limits of parameter resolution.

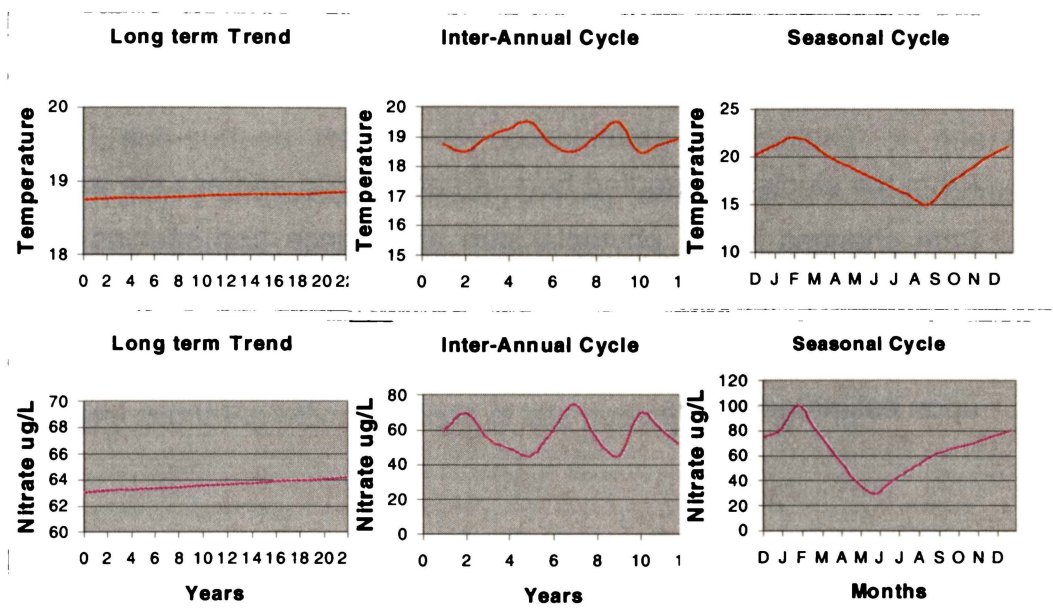


Figure 8-28: Annual averages and averaged annual cycles from PH50 and PH100 records, which indicates trends over 20 years are <1% of the seasonal signal for temperature and nutrients, whilst the inter-annual signal is ~15%.

Studies overseas have also identified the importance of defining the inter-annual signal in coastal waters to understand productivity patterns. Cross-shelf flux studies in New Zealand discussed in his study (and by Sharples, 1996; Zeldis et al, 2000) have similarly shown a strong correlation of the inter-annual signal to the intensity of shelf interactions and the phytoplankton response that results. Long-term studies of coastal upwelling patterns with respect to biomass on the west coast of the USA (Hsieh et al, 1995) have also shown ENSO signals are a strong determinant on upwelling patterns that control the intensity of seasonal productivity. Many smaller programs that have focused on parochial concerns of anthropogenic discharge in coastal waters, such as in Galicia,

NW Spain (Miranda and Fernandez, 2002), also detect these low frequency signals, but the study scope is often unable to provide adequate definition of their origin. Currently interest in cross-shelf dynamics and their effect on local productivity has generated large multi-disciplinary programs off Portugal and Canada's west-coast. These systems are heavily relied upon for their productivity to maintain fisheries but concern over anthropogenic stress, and the need to consider large-scale mariculture, generated the interest that developed these programs. This is similar to the experience that developed the study programs off Australia (ONPP) and New Zealand (NOEX) and supported the formulation of this thesis.

From the studies presented here, an attempt to address the issue of long-term changes in the phytoplankton abundance and species population, requires dedicated monitoring that encompasses both inter-annual variance and spatial consistency before any confidence can be placed upon estimated trends.

CHAPTER 9: CONCLUSIONS

9-1 MAJOR FINDINGS

A comparison of the various anthropogenic nutrient loadings to coastal waters off NSW, Australia, indicated loads from coastal sewage treatment plants (STPs) are large with respect to other discrete sources. Furthermore, the primary treated sewage continuously discharged from the three deepwater outfalls off Sydney is the dominant sewage source and delivers predominantly bio-available nitrogen to plankton in nitrogen limited sub-surface waters. By considering simulations of near-field effluent plume behaviour in relation to long-term ambient nutrient patterns, this study identified that the maximum risk of outfall impacts occurs in the upper half of the water column during late summer. Resolution of this anthropogenic influence on phytoplankton however is confused by the naturally occurring bloom periods of late summer and spring.

Patterns of spring phytoplankton bloom successions remain generally consistent with previous studies in Sydney coastal waters, with no discernible difference in phytoplankton biomass or species diversity. But, the high frequency of occurrence of both the chain-forming diatom *Thalassiosira spp.* and the 'red tide' heterotrophic dinoflagellate *Noctiluca scintillans* during the study period was unprecedented in these waters. These blooms however were reported throughout the study region during both spring and summer bloom seasons, and were clearly associated with coastal upwellings. In fact some companion plankton studies suggested dominant plankton growth was occurring outside the Sydney region with plankton abundances lower off Sydney and populations aged (not actively feeding/dividing). While studies often attribute changes in nutrient ratios for causing shifts in species abundance, long-term data and plume simulations did not suggest that the diluted effluent plumes from Sydney's deepwater outfalls result in major shifts in the ratio of dissolved inorganic nitrogen to dissolved phosphorus.

Although sewage discharges dominate the anthropogenic loads, flood discharges from coastal catchments may provide key periods for input to the coastal zone, when they override salinity gradients that buffer the estuary from coastal waters and flush highly turbid waters into a coastal boundary layer. These events not only serve as a discharge of nutrients that blueprint catchment geology (often contrary to coastal water nutrient composition), but also provide a mechanism to flush plankton stock harbouring within the estuary. The coastally bound layer that stored this anthropogenic discharge was monitored by SeaWiFs satellite imagery during the flood event study. While this imagery was designed for monitoring chlorophyll-a, a strong reflectance signal from floodwaters was observed. In combination with ground-truthing, the images can provide a powerful tool in estimating and monitoring relative loads from coastal catchments responding to a rain event. However this large discharged surface field (a 1-2 year flood event) did not result in enhanced phytoplankton levels in coastal waters during the course of this study. This may be because initial shading by floodwaters, and altered nutrient ratios (enhanced silica but reduced bioavailability of phosphorous), may have limited phytoplankton growth.

Coastal upwellings that caused intrusions of nutrient-rich slope-water to the euphotic zone were identified as the clear precursor of seasonal phytoplankton bloom patterns. From routine sampling undertaken off Sydney in 1978/79 and 1997/98, plankton responded to the coastal upwellings that lasted between 2-20 days during spring/summer. Correlation analysis confirmed elevated plankton counts were associated with current and 1-week lagged signals of bottom and surface temperature and nutrients, accounting for 60% of variability in biomass throughout the year. These nutrient-rich intrusions were associated with alongshore (southward) East Australian Current (90%) and high stratification, and only a negligible component was attributed solely to localised wind-driven upwelling off Sydney (3%). Temperature mooring data indicated upwelling frequencies of up to 10% occurred during October to April. Whilst the weaker spring signal was coherent across the 300 km study region during

August-October, the stronger summer signal in January-March was more localised. Over both seasons, wavelet analysis identified a peak associated with the 7-10 day weather-band period, that was in-phase and coherent over a 300 km alongshore study area, whereas low frequency signals up to ~40 days associated with the EAC, varied in coherence from 40 to 150 km alongshore. Fourier analysis of mooring and ORS data set (up to 10 years) affirmed that upwelling favourable winds were dominated by the 7-10 period, whilst the EAC signal had dominant seasonal and inter-annual energy peaks.

Topographic interaction with alongshore flow appeared as an important factor in generating localised uplifting, with clear increases in upwelling frequency southward (EAC downstream) of major changes in shoreline orientation. Two dominant bathymetric features off the NSW coast occur at Port Stephens and Jervis Bay, where changes of 50° between shelf and shoreline are evident. Subsequent study focus off Port Stephens, indicated dominant energy periods of 10-15 days were associated with cool water intrusions during formation of a ~30 km wide back-eddy in the lee of the Port.

Companion phytoplankton studies have implicated this back-eddy as an important upstream plankton source for the coastal region to the south. Through entrainment in the back-eddy off Port Stephens and by physical restraint within Jervis Bay, these significant anomalies in coastal topography subsequently influenced the behaviour of phytoplankton populations, with their retention capacity to “incubate” phytoplankton populations. Whilst similar lags in diatom peaks and subsequent *Noctiluca* growth (after critical prey mass of diatoms was achieved) followed the initial nutrient intrusion at both locations, the local flushing capacity determined the system's ability to return to ambient conditions. As a result, the defined 2-week diatom-dinoflagellate bloom succession sampled off Port Stephens during January 1997 was in contrast to a varied population of mixed reproductive stages that persisted well into March 1997 in Jervis Bay.

Anomalously strong upwelling sampled in the subsequent year (January 1998), combined with SeaWiFs satellite imagery, confirmed that the back-eddy off Port Stephens was incubating plankton prior to its southward dispersal by alongshore currents. This supported earlier observations by companion plankton studies in the previous two years. Upwelling favourable EAC dynamics complemented the upwellings predominantly driven by wind events in January 1998. Thus, the plankton streaming into the Sydney region was further enhanced by slope-water nutrient supplies, allowing coincident *Noctiluca* blooms to prevail throughout the study region to mid-February 1998.

Regionally, SST imagery indicated that an anomalous warm pool, associated with the strong 1997/98 El Niño, was present off the NSW coast in January 1998, and during the demise of this El Niño it contracted eastward across the Tasman to the New Zealand east-coast during February-March 1998. These warm surface water anomalies were associated with anomalously cooler coastal bottom waters and widespread algal blooms in both NSW and New Zealand coastal waters.

Unlike previous studies, *Thalassiosira* dominated diatom population and was linked to increased frequency in *Noctiluca*. The decrease in nutrient concentrations (relative to earlier studies) and associated warmer water was indicated as a reason for their dominance. The majority of visible algal blooms in NSW coastal waters have been harmless water discolorations, dominated by the more 'colourful' blooms of *Noctiluca scintillans* and *Trichodesmium*. While the latter is sourced from tropical ocean waters of the EAC, *Noctiluca* blooms were observed in offshore, coastal and estuarine waters including coastal lagoons of NSW.

While reports of *Noctiluca* have clearly increased off the NSW coast, in anthropogenically unstressed regions off New Zealand the incidence of reports are similarly high. Whereas in predominantly SE Asian waters this

species is often considered an indicator of eutrophic conditions, in our more temperate waters it is more likely attributed to oscillating climatic conditions that favour diatom species of a preferred *Noctiluca* diet.

The elevated biomass and nutrient levels experienced off the New Zealand NE coast (with respect to conditions off NSW) typically relate to predominant wind driven upwelling off New Zealand during late-winter and spring. As these prevailing winds weaken during summer, plankton populations typically decline, whereas off Australia strong EAC summer dynamics cause episodic coastal upwellings and intense bloom successions.

These general conditions can be modified by fluctuations of temperature and nutrient concentrations associated with ENSO, where signals manifested in (the NSW and NZ's NE coastal waters are out of phase. El Niño is manifested by respective warm-nutrient poor (NSW) and cool-nutrient rich (NZ) anomalies. The warm anomaly was shown to propagate eastward across the Tasman to New Zealand during the latter phase of an El Niño. The presence of this warm anomaly on both coasts was associated with extensive blooms of warm water species. Although wind driven upwellings off NE New Zealand are diminished during a La Niña, the SE winds may drive the EAC-NZ closer to the shelf. This can promote the scenario observed in January 1996, where the alongshore pressure gradient of the East Auckland Current interacted with shelf topography causing an upwelling cell to establish in the lee of Cape Brett.

The inter-annual ENSO oscillation caused temperature and nutrient fluctuations of $\pm 15\%$ of the seasonal signal in NSW coastal waters. These changes may be significant to shift plankton species, thus contributing to the unusually dominant diatom blooms of *Thalassiosira*, which led to extensive dinoflagellate blooms of *Noctiluca*.

Temperature and nutrient trends from the long-term records were estimated at $<1\%$ of the seasonal signal over a 20-year period, although

statistical tests indicated only phosphate showed any significant increase. As the anthropogenic loading to coastal waters is provided as predominantly nitrogen by outfalls this result, combined with the study's plankton observations, does not suggest that there is cause to accelerate reductions in discharges to the ocean. However, the study does highlight that retention areas such as embayments and re-circulation zones are more prone to extended plankton bloom, and therefore greater sensitivity is required when considering increasing anthropogenic input to these regions. If an increased phosphate loading is attributable to anthropogenic sources, it is likely to be coming from estuarine discharges and sourced diffusely from agricultural practices and catchment geology. Current popular interest on diffuse pollution as a key anthropogenic source provides a challenge for both research and regulatory agencies to resolve.

9-2 UNRESOLVED ISSUES

While overall hazards of problematic algal blooms have been shown to be low for the NSW coast, the potential risk for the future could be significant considering the continued introduction of pest species from ballast discharges, and increased frequency (and intensity) of inter-annual fluctuations due to climate change. Also, given the range of uncertainties associated with the large anthropogenic discharges and associated ambient entrainments caused by the deepwater outfalls, it is considered essential that ongoing monitoring is encouraged and adopted by regulatory agencies, in partnership with research groups so that any emerging effects can be resolved. This would also provide an ongoing mechanism to re-assess the management and cumulative inputs of nutrient discharges to coastal waters. This study has identified the following potential problem areas that ongoing research should address. These include;

1. On-going monitoring to resolve shifts in plankton species promoted by climatic oscillations or deepwater discharges,
2. Identifying the long-term sinks and nutrient cycling in coastal waters,

3. Coastal boundary layer storage of anthropogenic discharges
4. Laboratory studies to test extreme loading effects on regional algal populations

With a rapid increase in the interest of (and dependence on) marine aquaculture and existing harvesting of wild bivalves (pipis), predictive capabilities are clearly a means to manage this resource, and insure a return on the investment. Through the NSW EPA's Ocean Nutrient and Phytoplankton Project, and the large blooms that occurred within its lifespan, the enhanced interest in phytoplankton blooms assisted in the formation of a response network to inform growers and the public of an impending bloom threat. Presently the response occurs after a visible bloom has been sampled and identified and appropriate advice is distributed. Often this information may be provided too late for growers and stock are either banned or withheld from sale (held in depuration tanks). Ongoing losses however have prompted the need to develop a predictive capacity within the network. A range of monitoring options, which incorporate this ongoing scientific research, could allow this capacity to develop and are discussed in the following section. Although there are no current cost effective long-term strategies to routinely monitor phytoplankton activity, a number of useful tools that have emerged from this study could be adopted. These include;

1. Synoptic Monitoring
2. Simulated Monitoring
3. Direct Monitoring

Synoptic monitoring

Throughout the study program NOAA SST imagery was successfully employed to monitor coastal upwellings as a precursor (lags of ~1-2 weeks) to phytoplankton blooms. Towards the end of the program, this study took advantage of the launch of SeaWiFS in late 1997 to investigate the applicability of this method as a synoptic monitoring tool for coastal plankton populations. With respect to the sensors that preceded it, the SeaWiFS mission provided improved chlorophyll estimations in coastal

waters through the incorporation of additional bands, improved algorithms, and a dedicated calibration network. The new ocean colour satellite sensors currently scheduled for launch over the next few years will provide the increased spectral (from 8 to 250 bands) and spatial (from 1km to 100m) resolution needed to deal with the optical complexity of coastal waters. The existing NOAA and SeaWiFS data flows provide immediate opportunities for scientific investigations and, with caution, for monitoring spatial and temporal trends in phytoplankton activity (i.e. relative not absolute measures, unless well ground-truthed).

Simulated Monitoring

As diatoms are the initial bloom species in a succession, their identification and subsequent tracking allow predictions of target areas for the more potentially toxic dinoflagellates. To date, numerous attempts have been made to develop a hydrodynamic model to trace pollutants in the study region. But some of these either compromise the oceanic forcing, or the impact of coastal topography on circulation. As this study has shown, it is the interaction of these two that is the key to defining intrusions and retention times of eddies and embayments. An appropriate model driven with time series records (e.g. ORS, SST and coastal sea level) could be employed when monitoring identifies the initial intrusion event. Coupling these hydrodynamics to a eutrophication model can customise particle tracking to simulate specific characteristics of expected or identified bloom species. But for defensible results, this increases the complexity of the dedicated field campaign to calibrate and validate the simulations.

Direct Monitoring

While direct monitoring is the most costly option to adopt of the three, the use of either models or remote sensing requires a field component to calibrate their results. The value obtained from the long-term records used in this study is a clear indicator of their worth. Since the completion of this study, the Port Hacking 50 and 100m stations continue to be sampled on a monthly basis. It is clear from the studies presented here that monthly sampling is barely able to represent a distinct annual cycle for that year, and at least weekly samples are needed to resolve phytoplankton responses. Appropriate sampling resolution is being undertaken off the

New Zealand coast (since 1994), in direct response to the increasing phytoplankton threats on the mariculture industry. As a weekly sampling campaign is logistically demanding and costly to justify, remote monitoring through telemetered or serviced moorings is the most obvious direction to take. For this monitoring to be useful on an operational basis the degree of reliability of the system paramount and if poorly maintained could provide results less reliable than the simulated options. More complex data moorings that incorporate water samplers and analysers are now becoming more reliable as the increased pool of experience has reduced teething problems that previously plagued marketed systems. This study utilised robust moorings to monitor physico-chemical parameters, by using established relationships of simply measured parameters. The relation of temperature to nutrients proved to be good measure for identifying intrusions that could results in bloom conditions. Similarly it was shown that from the already established network of tide gauges, short-term anomalies in the alongshore pressure gradient could be resolved and associated to the coastal upwelling caused by the formation of the Port Stephens back-eddy. Both techniques have proved successful in identifying intrusions that led to algal blooms in the study region. When considering lags associated with the incubation of a bloom, these intrusion indicators could provide an early warning system to the aquaculture industry for heightened algal monitoring of local waters.

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APPENDIX 1: PAPER SUMMARIES

The following pages provide summaries of the material covered within papers which were produced during the ONPP, but have not been incorporated in this thesis.

Temporal abundance patterns of the red tide dinoflagellate, *Noctiluca scintillans* (Dinophyceae), along the south-east coast of Australia.

Dela-Cruz, J., Ajani, P., Lee, R..S., Pritchard, T.R. and Suthers, I.M.
Accepted in Marine Ecology Progress Series, February 2002.

CONTENTS

Weekly samples collected for 12 months from offshore Port Hacking (south Sydney) were analysed for a range of physical, chemical and biological measures including nutrients, phytoplankton and *Noctiluca scintillans*.

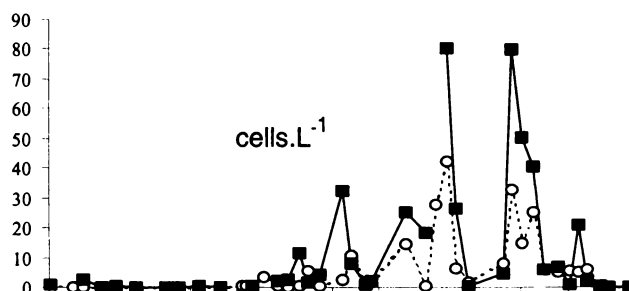
FINDINGS

Noctiluca was found year round but highest abundances were during the spring and summer

- Natural oceanic sources appear to drive rapid population growth (blooms) of *Noctiluca* at least during spring and summer:
- extensive red tides of *Noctiluca* often succeeded blooms of diatoms which were initiated by the uplifting/upwelling
- the stable isotope signature ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) of *Noctiluca* red tide cells suggested that growth of *Noctiluca*, at least during the spring and summer, was due to a single nutrient source such as slope water.

Despite these findings, it was still difficult to disregard the effects of anthropogenic nutrients on the growth of *Noctiluca*:

- the year round presence of *Noctiluca* was unprecedented for this region
- the frequency of occurrence of *Noctiluca* was sporadic up until the 1980's afterwhich *Noctiluca* red tides appeared to have increased in frequency and intensity
- a shift in the dominant diatom genera to *Thalassiosira* (an optimal food source of *Noctiluca*) may be the cause for the increase in *Noctiluca* numbers over time
- long term variability may have masked an anthropogenic signal



Abundance of Noctiluca scintillans at stations PH50 (solid squares) and PH100 (open circles) determined between March 1997& March1998. Peaks coincide with the three main uplifting/upwelling events.

Oceanic and Anthropogenic Nutrients and the Phytoplankton Response: Preliminary Findings

Pritchard, T.R., Lee, R.S. and Ajani, P.

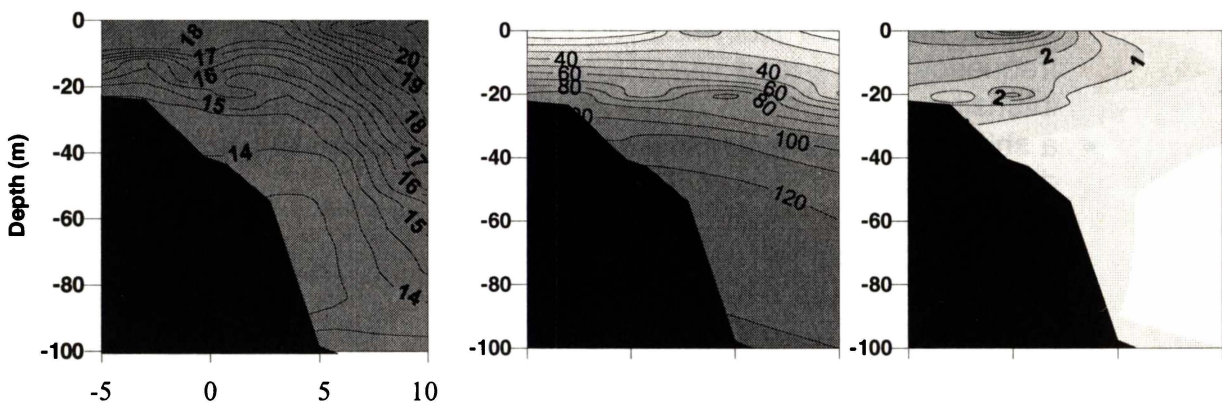
Pacific Coasts & Ports '97 Proceedings, V1, CAE Uni. Canterbury, New Zealand. 1997.

CONTENTS:

Early results indicating the relative importance of natural and anthropogenic nutrients on the development of phytoplankton blooms in coastal waters between Pt Stephens and Jervis Bay.

FINDINGS:

- Existing data indicate the potential for enrichment of surface ocean waters due to discharges from estuaries (especially nitrate and ammonia) and primary treated sewage outfalls (especially ammonia on those occasions when sewage plumes surface).
- High concentrations of nutrients in continental slope waters (especially nitrate and phosphate) and submerged sewage plumes (especially ammonia) illustrate the potential for vertical transport (upwelling or mixing) to dramatically enrich surface waters.
- Simultaneous physical, chemical and biological observations have demonstrated the critical importance of slope water intrusions in the development of a series of blooms in Jervis Bay during the period from mid-December 1996 to early March 1997.
- Furthermore, simultaneous observations off Port Stephens and Sydney suggest that this was a remarkably coherent regional phenomenon.
- These algal blooms occurred irrespective of proximity to outfalls and were associated with a large scale natural upwelling/uplifting processes



Temperature, Nitrate, and Chlorophyll-a 10 km offshore transects on 13 March 1997 at Jervis Bay relate upwelling temperature structure to nutrient intrusion and associated plankton enrichment in the embayment.

Relative Significance of Slope Water, Estuarine Discharges and Sewage Outfalls for Nutrients in Offshore Coastal Waters

Pritchard, T.R., Ajani, P., Andrew, D., Calfas, M., Holden, C., Lee, R.S., Linforth, S., and Rendell, P.

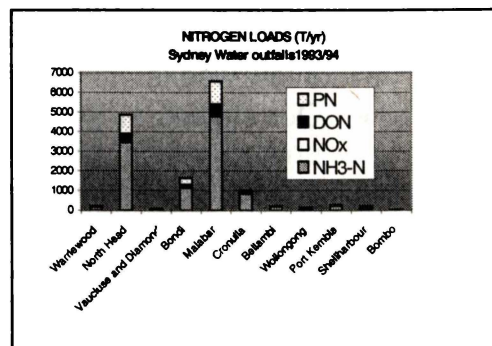
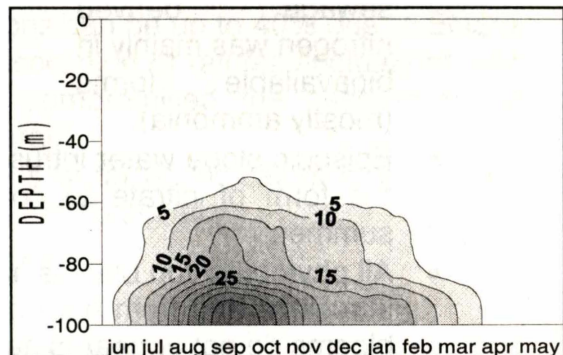
Coastal Nutrients Workshop Research Aiding Nutrient Management in Coastal Rivers and Estuaries 30-31 October 1997. Published by AWWA. ISBN 0-908255-42-X. , 1998.

CONTENTS:

Results indicating the relative importance of natural and anthropogenic nutrients on the development of phytoplankton blooms in coastal waters between Pt Stephens and Jervis Bay.

FINDINGS:

- Nutrient rich slope water intrusions appear to drive most phytoplankton blooms in the nearshore zone
- On average, coastal catchments appear to contribute minimal loads of nutrients except during major flood events
- In contrast to coastal catchments, discharges of sewage effluent from ocean outfalls are continuous and represent the principal source of ammonia ($\text{NH}_3\text{-N}$) to coastal waters in our study region
- Slope water (defined as $<14^\circ\text{C}$) occurs mainly during spring/summer in the bottom half of the water column [shown as % frequency occurrence based on long term monitoring off Pt Hacking]
- The vast majority of sewage derived nutrients come from just three outfalls (Sydney's deepwater outfalls) and most of these nutrients are in dissolved (bioavailable) forms. [PN = particulate nitrogen; DON = dissolved organic nitrogen; NO_x = oxidised nitrogen; $\text{NH}_3\text{-N}$ = ammonia]



Anthropogenic and Oceanic Nutrients in NSW's Dynamic Coastal Waters and Their Effect on Phytoplankton Populations

Pritchard, T. R., Lee, R. S. and Ajani, P.

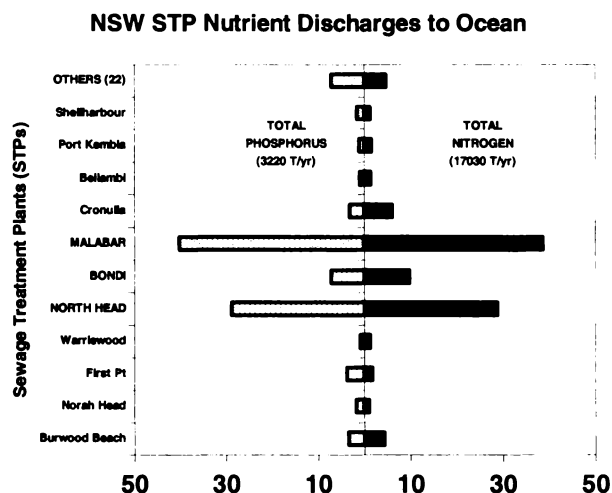
Pacific Coasts and Ports '99 Proceedings, Perth, W.A. 1999.

CONTENT

Results of a three-year, multi-disciplinary study was conducted by the NSW EPA to assess the relative importance of natural and anthropogenic nutrients on the development of phytoplankton blooms.

FINDINGS

- Sydney's three deepwater outfalls represented the principal, continuous, anthropogenic source of nutrients to NSW coastal waters. Effluent plumes generally remained submerged and sewage derived nitrogen was mainly in bioavailable forms (mostly ammonia).



- Episodic slope water intrusions were the principal source of nitrogen in the form of nitrate to coastal waters especially during spring and summer.
- All phytoplankton blooms investigated so far coincided with slope water intrusions and from our observations in the study area, phytoplankton blooms do not appear to be influenced by proximity to major outfalls.
- An understanding of mechanisms of slope water intrusion emerged from modelling exercises commissioned for this project and from direct observations. Slope water intrusions operated over (alongshore) length scales of hundreds of kilometres and over time scales of a few days to a few weeks.
- Our studies in Sydney's coastal waters indicate that patterns of spring phytoplankton bloom successions remain generally consistent with previous studies with similar phytoplankton biomass and diversity.
- However, the high frequency of occurrence of both the chain-forming diatom *Thalassiosira spp.* and the 'red tide' heterotrophic dinoflagellate *Noctiluca scintillans* during the study period was unprecedented in these waters.

Can climatic variability affect conclusions of short-term investigations off the NSW coast?

Lee, R.S., Pritchard, T.R., and Black, K.P.

(2002, in prep) *target journal of Environmental Management*

Presented at the 10th Annual NSW Coastal Management conference, 20-24 November 2000, Yamba, Australia

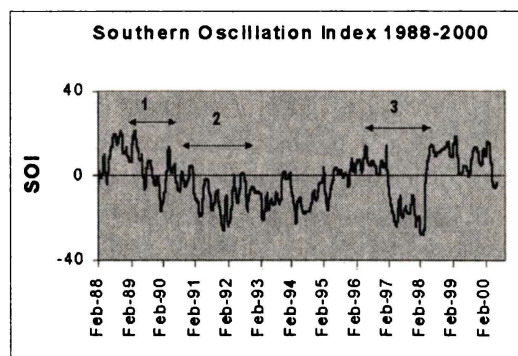
CONTENT

Short term studies are assessed for their relevance to reference data with respect to climatic variability. Case studies (Environmental Monitoring Program - EMP; Ocean Nutrient and Phytoplankton Project – ONPP) are provided to indicate how climatic variance can compromise interpretations.

FINDINGS

- Long-term records (since 1942) from monitoring stations offshore of Sydney (PH50 & PH100), indicate ~15% fluctuations of temperature and nutrients associated with the inter-annual cycle of El Nino occur with respect to the seasonal signal.
- Long-term trends from PH50 suggest changes over a 20 year period are <1% of the seasonal signal.
- From literature, rainfall fluctuations can be up to 40% due to ENSO. EMP studies showed strong association of rainfall fluctuations with ENSO of up to 60%, which compromised the assessment of improvements in sewage discharge.
- Expected long-term perturbations of target indicators in the ONPP were swamped by effects of the ENSO signal.

Studies in perspective with ENSO



Sydney EMP (1) pre-commissioning and (2) post-commissioning.
(3) Ocean Nutrient and Phytoplankton project

Southern oscillation index for the period of short term studies indicates a strong influence of ENSO activity.

DATA REPORTS

- **EPA (1998) Ocean Nutrient and Phytoplankton Project Data Report 1997-1998**
- **EPA (1997) Ocean Nutrient and Phytoplankton Project Progress and Data Report Second Season 1996-1997**
- **EPA (1996) Ocean Nutrient and Phytoplankton Project Progress and Data Report First Season 1995-1996**
- **Lee, R.S., Black, K.P., Sayce, A., and Sharples, J.,(1996). Cape Brett and Rimariki Island Transects 1995/96 Season report. NIWA report no. NOD602/2.**

CONTENTS

Documentation of instrumental methods and data collected during each year of the project mainly in the form of graphical and tabular summaries.

APPENDIX 2: THERMISTOR CALIBRATIONS

Table 1: Calibration #1 Jul-Aug 1997

Site	Thermistor ID	Offset deg. C	Thermistor ID	Offset deg. C	Thermistor ID	Offset deg. C
PS01	132126	0.12	137007	0.11	137008	0.03
PS02	132263	0.04	132264	0.09	137015	0.10
PS03	137021	0.07	137022	0.08	137019	0.20
PS04	137023	0.09	132265	0.00	137009	0.03
PS05	137025	0.10	137014	0.16	136999	0.06
PS06	137024	0.00	137016	0.09	137006	0.05
PS07	137010	0.00	137004	0.10	137003	0.06
PH01	132152	0.02	132125	0.09	132146	0.10
PH02	132139	0.03	132142	0.17	132143	0.06
PH03	137005	0.00	137012	0.18	137020	-0.03
PH04	137018	-0.02	132140	0.18	137001	0.05
PH05	132147	0.06	137011	-0.07	137013	0.04
PH06	132133	0.23	132138	0.18	137002	0.09
JB01	132130	0.06	132144	0.14	132149	0.24
JB02	132135	0.06	132141	-0.01	132145	0.18
JB03	132128	0.21	132131	0.01	132132	0.19
JB04	132129	-0.06	132134	0.21	132127	0.01
JB05	132137	-0.08	132148	0.23	132151	0.04
JB06	132136	0.06	93309	-0.02	132150	0.19

Table 2: Calibration #2 Feb-March 1998

Site	SN#	±°C	SN#	±°C	SN#	±°C	SN#	±°C	SN#	±°C
PS01	143401	0.05	143408	0.01	143411	0.00	160004	0.03	160014	-0.04
PS02	132263	-0.12	132264	-0.07	137015	-0.06	160003	-0.11	160012	0.04
PS03	137019	0.20	137021	0.07	137022	-0.56	162730	0.12	162734	0.13
PS07	137003	-0.09	137004	0.10	137010	0.11	160005	0.12	160009	0.18
PH01	132125	-0.06	132146	-0.05	132152	-0.13	160044	-0.01	160047	-0.03
PH03	137005	0.00	137012	0.02	137020	-0.03	162735	0.08	162736	-0.01
PH04	137140	0.02	132001	0.05	137018	-0.02	162732	0.05	162742	-0.02
PH05	132147	0.06	137011	-0.07	137013	0.04	162727	0.07	162740	-0.11
JB01	132130	0.06	132144	0.14	132149	0.08	160048	0.02	160049	0.07
JB03	132128	0.05	132131	0.01	132132	0.03	160045	-0.03	162728	0.06
JB04	132127	-0.14	132129	-0.06	132134	-0.10	160046	0.09	162741	-0.01
JB05	132137	-0.08	132148	0.07	132151	0.04	160043	-0.03	162739	0.04
JB06	162731	0.02	162733	-0.01	162738	0.00	162743	0.03	162737	-0.01

Table 3: Calibration #3 Sep-Oct 1998

Site	SN#	±°C	SN#	±°C	SN#	±°C	SN#	±°C	SN#	±°C
PS01	143401	-0.11	143408	0.01	143411	0.00	160004	-0.12	160014	-0.04
PS02	132264	-0.23			137015	-0.06	160003	-0.11	160012	-0.11
PS07	137003	-0.42			137004	-0.37	137010	0.11	160005	-0.03
PH01	132125	0.26			132146	0.75	132152	0.02	160044	0.33
PH03	137005	0.00			137012	-0.13	137020	-0.03	162735	-0.07
PH04	137140	0.02			132001	-0.11	137018	-0.02	162732	0.05
PH05	132147	0.06			137011	-0.07	137013	-0.11	162727	-0.08
JB03					132131	0.01	132132	-0.12	160045	-0.19
JB04	132127	-0.31			132129	-0.06	132134	-0.10	160046	-0.06
JB05	132137	-0.08			132148	-0.08			160043	-0.03
									162739	0.04