Climate and ocean trends of potential relevance to fisheries in the New Zealand region

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EXECUTIVE SUMMARY

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***New Zealand Aquatic Environment and Biodiversity Report No. 90.* 202 p.**

This report contains 11 categories of climatic and oceanographic indices of potential relevance to New Zealand fisheries: 4 climate (Interdecadal Pacific Oscillation (IPO); Southern Oscillation Index (SOI); surface wind and pressure patterns; New Zealand average air temperatures) and 6 oceanographic (sea surface temperature (SST) from coastal monitoring and satellites; upwelling; ocean temperature; sea surface height (SSH); ocean colour (chlorophyll, Chl); and acidification. Where possible, links between some of these categories of indices are described. No indices are currently available for ocean currents, and only one short series is available for acidification, so summaries of the current state of knowledge are presented. The report also includes a glossary of the climatic and oceanographic terminology used.

The spatial and temporal scales of the indices presented vary depending on whether they have local application (e.g., upwelling, air temperature, ocean temperature, coastal SST), or are on a regional or New Zealand wide scale (e.g., synoptic weather patterns, SST); whether they are relevant on both short and long time scales (e.g., synoptic weather patterns, ocean temperature, Chl, SST) or over annual or greater periods (e.g., SOI, IPO). Globally, many of these types of indices have been found to be correlated with a variety of fish population processes, including recruitment fluctuations, growth, distribution, productivity and catch rates. In the New Zealand region, the strength and frequency of prevailing westerlies can be expected to drive the temperature and availability of nutrients for primary productivity in the upper part of the ocean, because of their effect on vertical mixing of the water column and upwelling. This will in turn impact on secondary zooplankton production and food availability for various fish life history stages. Recent trends in some of the key ocean climate indices in New Zealand waters are as follows:

- The Interdecadal Pacific Oscillation (IPO) is a Pacific-wide reorganisation of the heat content of the upper ocean and represents large-scale, decadal temperature variability, with changes in phase (or “regime shifts”) over 10–30 year time scales. In the last decade, regime shifts occurred in 1925, 1947, 1977 and 2000. The latest shift is most clearly seen in SST (e.g., at coastal stations off Tauranga, Napier and Portobello, and from regional SST from the Tasman Sea and subtropical area to the east of New Zealand) and ocean temperatures to 500 m depth on two transects to the west and north of New Zealand. In the North Pacific in particular, but also increasingly in the South Pacific, regime shifts have been found to be correlated with major changes in fisheries, plankton, and marine mammal and seabird populations. Our ability to detect any such changes in New Zealand is limited because most of our fishery abundance monitoring indices extend back only to about 1990 and therefore cover only one regime shift.

- The Southern Oscillation Index (SOI) is a measure of the difference in mean sea-level pressure between Tahiti (east Pacific) and Darwin (west Pacific) and is related to the strength of the trade winds in the southern hemisphere tropical Pacific. The cycles of La Niña (positive phase) and El Niño (negative phase) events are irregular and occur over three to seven year time scales. In El Niño events, New Zealand experiences increased westerly and southwesterly winds, cooler sea surface temperatures, and enhanced upwelling, which will affect primary production. El Niño events are likely to be less frequent during the negative phase of the IPO which began in about 2000.

- Surface wind and pressure patterns of relevance to fish population processes may occur over short time scales (e.g., immediate effects on fish catchability) as well as over seasonal and annual time scales. Some general trends, such as more frequent zonal westerly winds and southerly winds, are associated with the positive phase of the IPO and more frequent El Niño events.

- Sea surface temperature (SST), sea surface height (SSH), air temperature, ocean temperature to 800 m depth, SST, and SSH all exhibit some correlation with each other over seasonal and interannual time scales. Air temperatures have increased 0.5–0.9 °C since 1900, mostly during the mid 1950s. Any effects of global warming from the late 1970s to 2000 may have been lessened by the positive phase of the IPO when more frequent El Niño events would be expected to reduce average temperatures. Many of the temperature series show increases during the current negative phase of the IPO which started in 2000, as well as a significant warming event during the late 1990s. All of the SSH series show an increase since the mid 1990s.

- Ocean colour (chlorophyll production) and upwelling indices are available from 1997 and 1993, respectively. They will be important time series to monitor for the future because they potentially have a more direct link to secondary zooplankton production and food availability for various fish life history stages. At this stage these series require more detailed development and validation with respect to other ocean climate variables.

- Acidification (increase in CO_2 concentrations) of the oceans has paralleled the increase in atmospheric CO_2 globally, apparent to an average depth of about 1000 m. The resulting reduction in carbonate availability will affect organisms that produce shells or body structures of calcium carbonate, plankton productivity will be stimulated and physiological stress increased. Organisms most likely to be affected are those at the base of the food chain (bacteria, protozoa, and plankton), coralline algae, corals, echinoderms, molluscs, and possibly cephalopods (e.g., squids) and high-activity pelagic fish (e.g., tunas). New Zealand has one short time series (off Otago, started in 1998) and is planning development of new monitoring programmes.

1. INTRODUCTION

General overview

Climatic and oceanographic conditions play an important role in driving the productivity of our oceans and, in particular, the abundance and distribution of our fisheries. Internationally there has been significant progress in linking trends in climate and ocean conditions with changes in fish species (e.g., North Sea cod: Otterson et al. (1994), Myers (2001), Beaugrand et al. (2003), Brander (2004), ICES (2004), Perry et al. (2005); Northeast Pacific: alternate sardine and anchovy fluctuations, Francis & Hare (1994); multi-species review by Francis et al. (1998)). On an ecosystem scale, ocean climatic and oceanographic conditions affect ecosystem productivity and dynamics both from bottom-up trophic processes (through short- and long-term variability in primary and secondary production) as well as from the top-down trophic processes (through variability in the abundance and spatial distribution of key predators. Bottom-up examples included: the increasing abundance of tropical and subtropical planktonic foraminifera in the California currents, reflecting a warming trend during the 20th century in the Northeast Pacific (Field et al. 2006); the relationship between larval marine fish survival (sablefish off the British Columbia coast), zooplankton (copepod) abundance, and climate conditions (Aleutian Low intensity) from 1965–80 (McFarlane & Beamish 1992); and the link between salmon and zooplankton production (Francis & Hare 1994). Worm & Myers (2003) found top-down cod–shrimp interaction in the North Atlantic, with cod biomass positively related with ocean temperature but the strength of the cod–shrimp relationship declining with increasing mean temperature.

Significant variations in ecosystems (both gradual and sudden) often coincide with changes observed in ocean and atmosphere parameters (Botsford et al. 1997, Mantua et al. 1997, Anderson & Piatt 1999, Hare & Mantua 2000, Peterson & Schwing 2003, Polovina 2005). For example, Mantua et al. (1997) found that dramatic shifts in salmon production regimes in the North Pacific corresponded to a recurring pattern of interdecadal climate variability they named the Pacific Interdecadal Oscillation (PDO). While such phenomena have been seen for many different fish stocks in various parts of the world, the mechanisms that link large-scale ocean and atmosphere dynamics to changes in population abundances are not always clear (Botsford et al. 1997; Baumann 1998), and the relationships are not always constant over time (Solow 2002). Biological variables often show a broad distribution of shifts over time, which are consistent with different types of responses to climate for different ecosystem elements and the importance of time lags in response to changes in physical forcing (Overland et al. 2008).

Ecosystem changes related to regime shifts [or climate change] are not necessarily detrimental to the ecosystem as a whole and may in fact be drivers of high productivity. They also provide an opportunity for alternative management approaches such as optimising opportunities of inherently erratic but productive systems (Bakun & Broad 2003). Sustainable management of fish resources will be enhanced if such phenomena and their impacts are recognised and better understood.

New Zealand's climate is strongly influenced by its position in the mid-latitudes of the southern hemisphere. The passage of transient anticyclones and depressions in the prevailing westerlies, and the larger-scale climate patterns, modulate the strength and location of the westerly wind belt. In middle latitudes much of the seasonal to interannual variability in the oceanic mixed layer is thought to be forced by changes in the atmospheric circulation (Lau 1997), through changes in heat and momentum transfers at the ocean surface. Relevant large scale climate patterns influencing the New Zealand climate include the El Niño-Southern Oscillation (ENSO) cycle (Salinger & Mullan 1999; Bhaskaran & Mullan 2003), the Interdecadal Pacific Oscillation (IPO, Salinger et al. 2001), and the Antarctic/high latitude circulation and Southern Annular Mode (Kidson 2000; Renwick & Thompson 2006). Changes in the magnitude and sign (negative-positive) of such hemispheric-scale patterns of climate variability affect the direction and strength of the low-level wind circulation over New Zealand, and hence the surface ocean conditions. The wind circulation affects the availability of nutrients for primary productivity in the upper part of the ocean through its effect on vertical mixing of the water column and upwelling. Wind circulation also affects sea surface temperatures.

New Zealand's climate, climate variability, and climate prediction have been the subject of increasing levels of research in recent years. Oceans and ocean variability are less well understood and the links between the atmosphere and oceans have started being modelled only in the last decade. The availability of satellite information in recent years has greatly enhanced research and monitoring in both disciplines.

This baseline report provides a framework for summarising and updating trends in climatic and oceanographic conditions to provide an environmental context for fisheries and marine ecosystem resource management in the New Zealand region.

The New Zealand fisheries context

The key drivers that are likely to influence fisheries and ecosystem productivity in New Zealand include the presence of warm subtropical surface waters to the north, cooler subantarctic waters to the south, and localised bathymetry (rises, seamounts, canyons) that affects current movements and mixing.

Studies linking climate, oceanography, and fisheries in New Zealand are limited by time series that are, at best, only several decades long. Any relationships are likely to be highly complex and variable and may change over time in response to regime shifts, climate change, and fishing pressure. Impacts of climate variability and change on fish populations are likely to show response lags or step-like changes that are difficult to predict. Significantly long time series are required to develop relationships that are statistically robust, such as studies on sardine and anchovy catch data from 1920 and resource surveys from 1950 (Francis & Hare 1994).

In New Zealand, the lack of long time series applies to both indices of fish abundance and distributional data, as well as to some of the oceanographic indices derived from remote sensing methods, such as sea surface temperature (SST), sea surface height (SSH), and ocean colour. Monitoring of ocean acidification and modelling of the variability in ocean currents are even more recent research areas that are likely to be of relevance to understanding changes in marine ecosystems in the future, but are of limited application in the short term..

Some progress has been made in linking climate and recruitment or abundance for a number of key New Zealand marine fish species. Most studies have investigated correlations between climate and recruitment, including: hoki (Livingston 2000, Bull & Livingston 2001, Francis et al. 2006); snapper (Francis 1994a, 1994b); southern gemfish (Renwick et al. 1998); red cod (Beentjes & Renwick 2001); southern blue whiting (Hanchet & Renwick 1999, Willis et al. 2007); and rock lobster (Booth et al. 2000). Studies that have considered climate effects on fish distribution or catch rates include: school sharks (Ayers et al. 2006); orange roughy (Taylor 2001); bluefin tuna (Uddstrom et al. 2003); swordfish (Unwin et al. 2005a); albacore tuna (Unwin et al. 2005b); the Chilean jack mackerel invasion of New Zealand waters (Taylor 2002); and interannual variation in trawl surveys and commercial fishery catch rates (Francis et al. 2003). Recent studies that have also considered links between ocean currents and dispersal of life history stages of rock lobster (Chiswell & Booth 1999, 2005, 2007), orange roughy (Dunn et al. 2009b) and Ross Sea toothfish (Hanchet et al. 2008).

More recently, Dunn et al. (2009) carried out a meta-analysis of abundance and catch trends in New Zealand fisheries in relation to key 20 climate indices for 56 (mostly commercial) New Zealand fish species and time series from as short as 5 years to a maximum of about 30 years. They found no evidence for any consistent changes in the relative abundance or catchability of the warmer versus colder water species, nor were there any consistent responses to climate within each of these groups. They did find significant correlations for a number of individual species and, after removing potentially spurious relationships (e.g., unidirectional trends, conflicting trends between different indices for the same species), they concluded that at least six species (elephantfish, school shark, red gurnard, stargazer, hake, and tarakihi) relationships were worthy of more detailed investigations, including development of hypotheses and more rigorous statistical analysis. They also found relatively consistent patterns in cyclical fluctuations observed in some of the longer trawl survey time series may also warrant further investigation. Species included oblique banded rattail, Bollons's rattail, and ling in the summer Chatham Rise surveys, and banded rattail, Oliver's rattail, pale and dark ghost shark in the spring Sub-Antarctic surveys. In general, the meta-analysis supported findings of earlier studies on gemfish, red cod, and snapper, although the areas may be different and the exact variables chosen may be different but possibly aliasing similar things (e.g., SST and SSH for gemfish).

Most studies (in New Zealand and internationally) that have attempted to correlate fish abundance or recruitment indices with climatic or oceanographic conditions have involved very limited statistical cross-validation or hypothesis testing of causal relationships. In New Zealand, some success has been achieved recently in understanding causal relationships in localised areas, such as the effect of climate on nutrient supply and yield of Marlborough Sounds mussels (Zeldis et al. 2008) and for some fish species, there have been attempts to generate hypotheses and explore possible causal relationships statistically (e.g., hoki, Francis et al. 2005, 2006). Progress is possible in the future with longer time series, more exploration of testable hypotheses using non-linear relationships, and stochasticity built into modelling of the biological or ecological responses to environmental stressors. Studies that have recorded significant statistical relationships between fish abundance (either biomass or recruitment indices) in New Zealand waters are listed in Table 1. This table includes only the Dunn et al. (2009) results listed as "notable" by the authors.

This document provides time series for a suite of climatic and oceanographic indices that are potentially relevant to New Zealand fisheries and marine ecosystems. A broad suite is included even though statistically significant linkages or causal relationships are difficult to demonstrate. The role that many of these variables may play in ecosystem changes or fish population abundance trends is likely to be very complex and probably require more sophisticated methods of analysis than those assuming linear relationships among variables. The length of time series and presence of oscillations (i.e., not one-way trends) in indices are also important. Future linkages may be determined as longer time series of appropriate indices (both fisheries and ocean climate) become established and understanding of process or analytical methods improve.

Objectives of this report

Overall objective

1. To summarise, for fisheries managers, climatic and oceanographic fluctuations and cycles that affect productivity, fish distribution and fish abundance in New Zealand.

Specific objective

1. To provide an up-to-date overview of climatic trends and cycles and how they affect New Zealand oceanographic conditions, fishstock abundance and distribution.

Table 1: Studies linking climate or oceanographic factors to trends or cycles in fish abundance or recruitment (YCS, year class strength) in New Zealand waters. The sign refers to the nature of the relationship. Three letter species codes refer to Fishstock or Quota Management Areas; SOI, Southern Oscillation Index; Temp., temperature; SST, sea surface temperature; SSH, sea surface height; YCS, estimated year class strength; Chat. Rise, Chatham Rise

Species and Fishstock area	SOI	Temp. SST /air	SSH	Surface/wind pressure[a]	Period of fisheries data / YCS	Reference
Elephantfish ELE3		+SST	+		1990–2006	Dunn et al.2008
Gemfish SKI 7		+SST		– SW winds	1982-1996	Renwick et al.1998
Hake HAK3 YCS HAK4	 –		– 	 – Blocking	1992–2006 1975–2000	Dunn et al.2008 Dunn et al.2008
Hoki YCS Chat. Rise biomass Chat. Rise YCS	–SOI – 	–SST –SST –SST	 – 	W / SW flow along WCSI – Blocking, + M1, +Z4	1978–1996 1992–2006 1975–2005	Bull & Livingston 2001[b] Dunn et al.2008
Red cod RCO 3 RCO 7	– 	–SST –SST		 + Trough	1971–1998 1992–2005	Beentjes & Renwick 2001 Dunn et al.2008
Red gurnard GUR2 GUR7 FMA9	 + –	 –SST		+ Trough – M1 	1990–2001 1992–2005 1986–1996	Dunn et al.2008 Dunn et al.2008 Dunn et al.2008
Rock lobster				+Trough, +HSE	Various 1979–1998	Booth et al.2000
School shark SCH1 SCH8	– 	–SST 		 + Trough, –Zonal	1990–2002 1990–2006	Dunn et al.2008 Dunn et al.2008
Snapper SNA1 SNA2, 7		+air +air			1983–1999 1978–1995	Francis 1994a, 1994b Gilbert & Taylor 2001
S. blue whiting 6C				– PC1, – spring HNW	1997–2002	Willis et al. 2007, Hanchet & Renwick 1999
Stargazer STA7	+	+SST		Blocking	1990–2006	Dunn et al.2008
Tarakihi TAR2		+SST			1990–2002	Dunn et al.2008

a see Section 3.3 of this report for a description of the terms used for surface and wind pressure; PC1 relates to a high pressure system over Campbell.
b This study is cited, although subsequent analysis (Francis et al. 2005, 2006) of a longer time series did not find significant relationships.

2. METHODS

This project reviews existing climate and oceans literature and compiles available data and time series that will identify trends and changes in New Zealand ocean climate of potential relevance to fisheries management. Time series of some of these data are already available in a form that is readily interpretable and can be used to relate to fisheries indices (e.g., air temperatures, wind and pressure patterns). Other data types required development of relevant indices (e.g., such as removal of seasonal signals to obtain annual trends). The Currents and Acidification sections are primarily summaries of the current state of knowledge. There are 12 sections that fall into 2 categories (Table 2): Climate, with 4 separate sets of indices; and Oceans, with 7 sets of indices and 1 information summary.

The report includes the following:

- explanation of the fundamental concepts in each discipline
- a summary of relevant New Zealand literature

- description of the indices developed (see summary in Table 2)
- description of trends or cycles in indices and correlations with other indices in the report
- a glossary of terminology used (Appendix 1)

Table 2: Summary of climatic and oceanographic data and indices presented, EOF, empirical orthogonal function; SD, standard deviation; pCO2, particulate carbon; pH, acidity;

Category	Section	Sub-category	Data or indices
Climate	3.1	Interdecadal Pacific Oscillation (IPO)	Annual
	3.2	Southern Oscillation Index (SOI)	Seasonal, annual
	3.3	Wind and pressure patterns	Monthly
	3.4	Air temperatures	Kidson synoptic types Trenberth indices
Oceans	3.5	Coastal Sea Surface Temperatures (SST)	Monthly
	3.6 App 2 App 3 App 4 App 5	Sea Surface Temperatures (SST - satellites)	Regional anomalies Monthly mean climatologies Rotated EOFs seasonal anomalies Rotated EOFs spatial anomalies Monthly means and anomalies
	3.7	Upwelling	Monthly
	3.8	Ocean temperature	Eastern Tasman, seasonal Northern NZ, seasonal
	3.9	Sea surface height (SSH)	Regional monthly
	3.10	Ocean colour (Chl a)	NZ mean and SD NZ EOF Locations along longitudinal gradients Locations relevant to fisheries
	3.12	Acidification	pCO2 and pH, Otago

Fisheries indices do not form part of this review, and the references in Table 1 should be referred to.

3. RESULTS

Climate variables

Climatic indices presented here include the Interdecadal Pacific Oscillation (IPO), the Southern Oscillation Index (SOI), surface wind and pressure patterns, and air temperatures. Many of these indices are available on 50–100 year time scales.

3.1 Interdecadal Pacific Oscillation (IPO)

The IPO is a Pacific-wide reorganisation of the heat content of the upper ocean and represents large-scale (near global) interdecadal sea surface temperature variability, similar to a long-lived El Niño-like SST pattern (Power et al. 1999, Salinger et al. 2001, Folland et al. 2002). The IPO is characterised using the time series of the 3rd Empirical Orthogonal Function (EOF3) of 13 year lowpass filtered global SST (Folland et al. 2002), projected onto annual data. The North Pacific manifestation of the IPO is similar to the Pacific Decadal Oscillation (PDO). The mechanisms causing IPO / PDO variability remain unclear (Mantua & Hare 2002, Power et al. 2006). The IPO time series is available from 1900 to June 2008 and is best represented as annual means, usually smoothed over 13 years (Figure 1).

Trends/cycles and relevance to fisheries

The IPO changes from its positive to its negative polarity about every 20–30 years and changes in polarity ("regime shifts") take 6–7 years to detect, given the very low-frequency nature of the oscillation. When the IPO is in the positive polarity, El Niño events tend to be more frequent and stronger, while in the negative polarity, El Niño events are weaker, and La Niña events are more prominent. Hence, in the positive phase (e.g., late 1970s–2000), New Zealand tends to experience periods of enhanced westerlies, with associated cooler air and sea temperatures, an enhanced west-east precipitation gradient (wetter than normal in the west and south, and drier than normal in the east and north) and enhanced upwelling on western coasts (Power et al. 1999, Salinger et al. 2001, Folland et al. 2002). As indicated in the introduction, these factors all affect nutrient availability and primary productivity in the upper ocean.

Mantua & Hare (2002) noted that several independent studies find evidence for just two full PDO cycles in the past century: "cool" PDO regimes prevailed from 1890 to 1924 and again from 1947 to 1976, while "warm" PDO regimes dominated from 1925 to 1946 and from 1977 through (at least) the mid 1990s. There is evidence of a regime shift into the negative phase of the IPO in about 2000, but the monthly indices have been highly variable and the trend is still only slightly negative. It is not an abrupt change as seen in the late 1940s and 1970s.

There is a strong link between the PDO and some fisheries, in fact the PDO was first recognised from a study by Mantua et al. (1997) who found that Pacific salmon catches in Alaska varied inversely with catches from the United States west coast during the past 70 years and that these changes were related to climate forcing. Temporally, both the physical and biological variability were best characterised as alternating 20–30 year long regimes punctuated by abrupt reversals, with ocean conditions from 1977 to the early 1990s generally favouring Alaska stocks and not west coast stocks. There were important implications for management efforts focused on increasing west coast Pacific salmon production and recovery of at-risk (threatened and endangered) stocks.

Although most literature on fishery impacts of the PDO is on northern hemisphere examples, there is a growing body of evidence demonstrating impacts in the southern hemisphere, with important surface climate anomalies over the mid-latitude South Pacific Ocean, Australia, and South America (Mantua & Hare 2002). Interdecadal changes in Pacific climate have widespread effects on species production and assemblages, such as Pacific salmon, Alaskan groundfish, sardines off Japan, California, Chile, and Peru, halibut recruitment, primary and secondary production, Central and Eastern North Pacific zooplankton, marine species assemblages in the Gulf of Alaska (from a complex dominated lower trophic level forage species to on dominated by higher trophic level groundfish), and marine mammal and Pacific seabirds (see review by Mantua & Hare (2002)).

New Zealand studies to date that have attempted to link New Zealand fisheries with the IPO are problematic because most fisheries monitoring time series (other than just catch landed) are not long enough to cover more than one phase, i.e., they are predominantly from 1990.

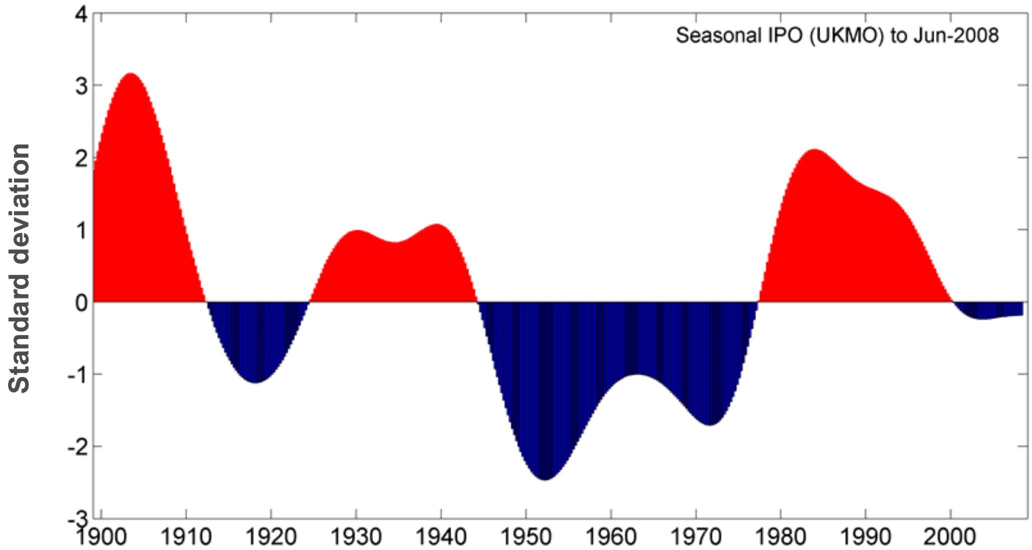


Figure 1: The Interdecadal Pacific Oscillation index, using a 13 year average (source: United Kingdom Meteorological Office, UKMO).

3. 2 Southern Oscillation Index (SOI)

The El Niño-Southern Oscillation (ENSO) cycle in the tropical Pacific has a strong influence on New Zealand. ENSO is described here by the Southern Oscillation Index (SOI), a measure of the difference in mean sea-level pressure between Tahiti (east Pacific) and Darwin (west Pacific). It is related to the strength of the trade winds in the southern hemisphere tropical Pacific. When the SOI is strongly positive, a La Niña event is taking place and New Zealand tends to experience more north easterlies, reduced westerly winds, and milder, more settled, warmer anticyclonic weather and warmer sea temperatures. When the SOI is strongly negative, an El Niño event is taking place and New Zealand tends to experience increased westerly and southwesterly winds and cooler, less settled weather and enhanced along shelf upwelling off the west coast South Island and north east North Island (Shirtcliffe et.al. 1990, Chang & Mullan 2003, Zeldis et al. 2004). The SOI is available monthly from 1900 (available since 1876, Mullan (1995)) to May 2008. However, it is best represented as seasonal (3-monthly running means, Figure 2a) to annual (May–April) averages (Figure 2b).

Trends/cycles and relevance to fisheries:
The ENSO cycle is irregular, with El Niño events occurring every 3–7 years. Most recently, 5 of the last 7 years have been in the negative phase of the SOI whereas the preceding 3 years were positive. There are no indications of long-term trends in the ENSO cycle (associated with anthropogenic climate change, or other causes), and future climate change projections give no strong indications of

ENSO trends in future. However, the ENSO cycle is naturally modulated by the IPO. Paleoclimate evidence shows that, over the past several thousand years, there have been centuries-long periods of little or no ENSO activity, and periods of strong and regular ENSO activity. The causes of such behaviour, and its implications for the future, are current climatological research questions.

New Zealand studies (Table 1) have found links between SOI and fisheries indices, for example, hake, hoki, red cod, red gurnard, school shark and stargazer (Beentjes & Renwick 2001, Bull & Livingston 2001, Dunn et al. 2009a). Other more detailed studies have mapped the occurrence and extent of seasonal upwellings, often linked to El Niño, and the associated nutrient flux and enhanced phytoplankton growth (Zeldis et al. 2004, 2008, Willis et al. 2007). For example, increased mussel yield in Pelorus Sound has been linked to El Niño, upwelling and increased phytoplankton biomass (Zeldis et al. 2008). Major harmful algal blooms have also been linked to El Niño and La Niña events (Chang & Mullan 2003).

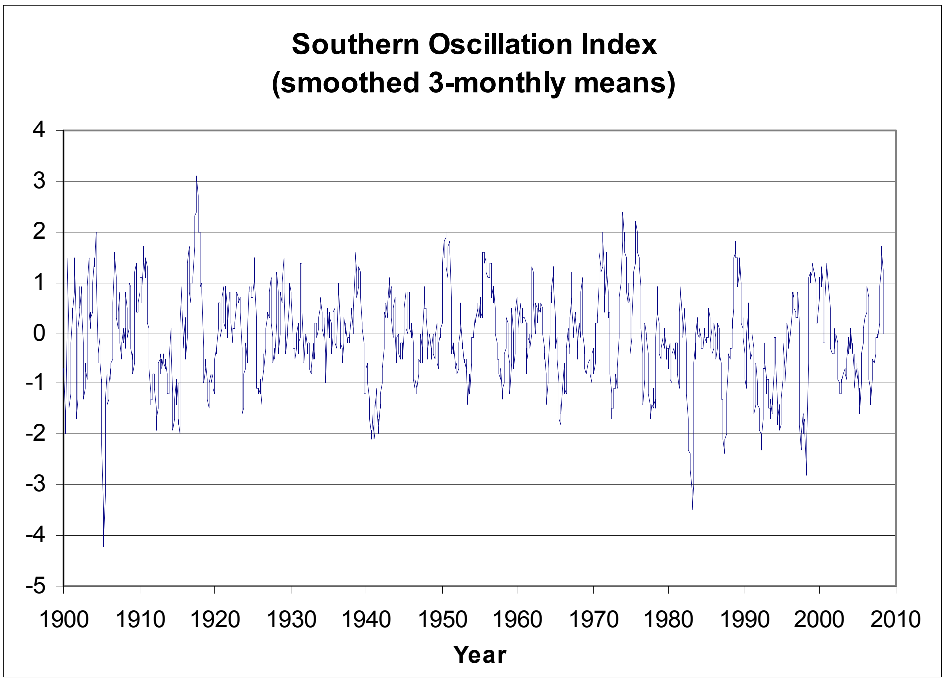


Figure 2a: The Southern Oscillation Index, 3-monthly running means.

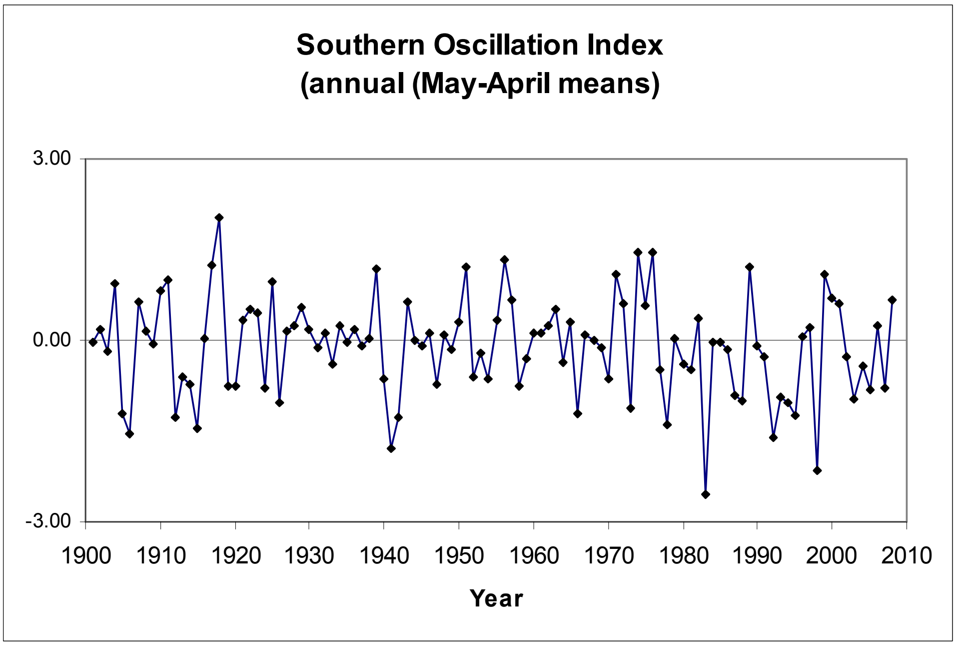


Figure 2b: The Southern Oscillation Index, annual means (May–April).

3.3 Surface wind and pressure patterns

Weather type frequencies and pressure/wind indices are related to surface ocean conditions, largely through implied surface ocean heat fluxes. More settled, low-wind periods tend to be associated with increased sea-surface temperatures, while the windier more disturbed flows tend to be associated with cooler seas. Coastal upwelling is modulated by along-shore wind flows, hence there are relationships between the various weather types and wind flows and upwelling on exposed coasts.

3.3.1 Synoptic weather pattern frequency (after Kidson 2000)

The 'Kidson weather types' are defined on a 12-hourly basis, describing the daily sequence of weather over New Zealand in terms of a set of 12 types of weather maps, or surface wind flows (Figure 3). They are available daily from 1958 to December 2007 and presented here as annual smoothed (13-month running means) frequencies of occurrence.

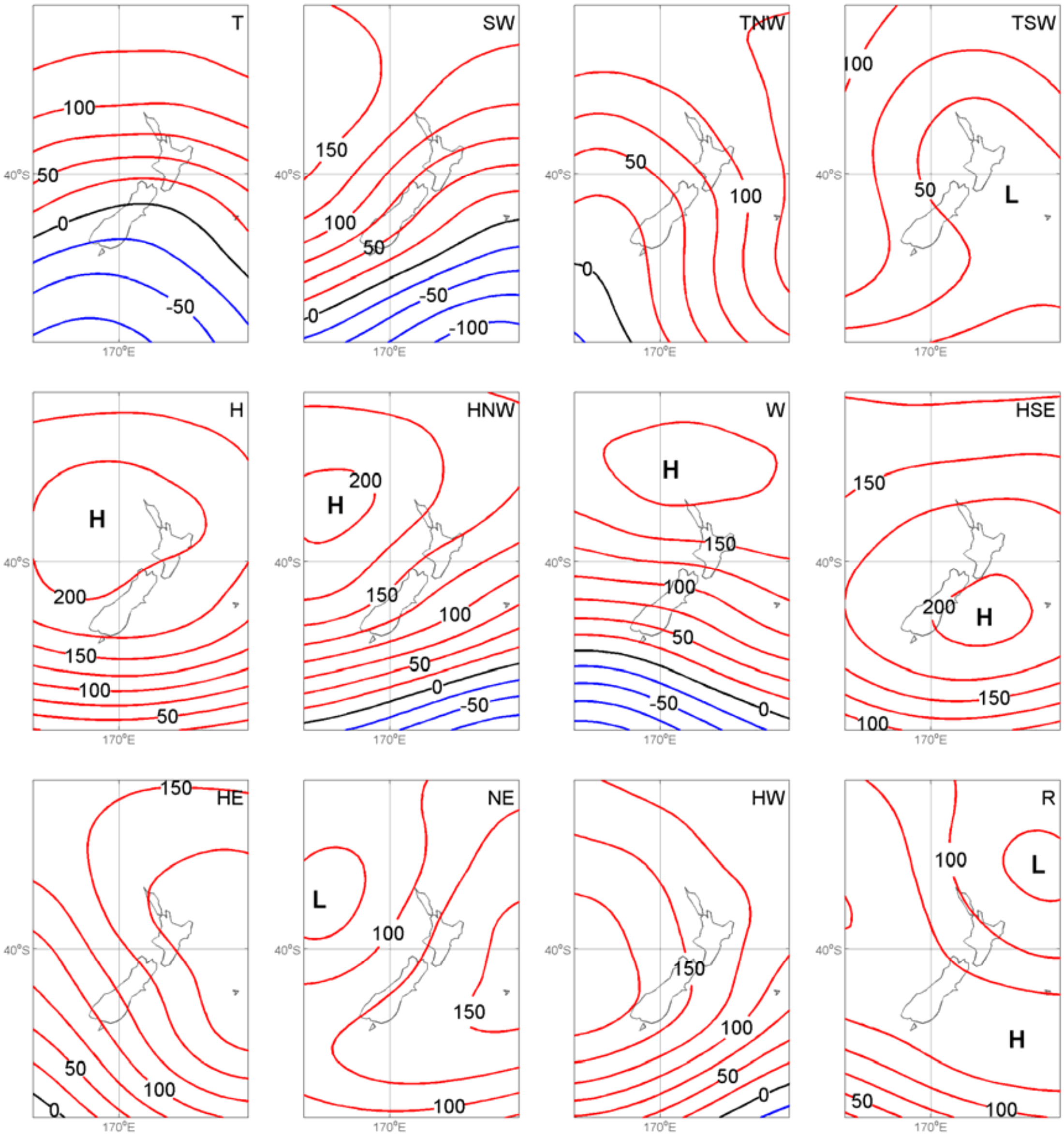


Figure 3: The 12 "Kidson' synoptic weather types (T, trough; SW, southwesterly; TNW, trough to the west; TSW, trough in southwest flow; H, high; HNW, high to the northwest, W, westerly; HSE, high to the southeast; H, high to the east; NE, northeasterly; HW, high to the west of the South Island; R, ridge.

From cluster analysis of the monthly frequencies of these patterns Kidson (2000) defined three 'regimes'.

The 'Trough' Kidson regime (top row of Figure 3, types T, SW, TSW, TNW) is characterised by frequent pressure troughs over and east of the country. It is linked with high rainfall, and below-normal temperatures in the south. The Trough regime typically brings wet, cool and cloudy conditions to most of the country and is less frequent in autumn.

The 'Zonal' Kidson regime (most of the middle row of Figure 3, types H, HNW, W) is characterised by intense anticyclones north of 40° S, and strong zonal (westerly) flow to the south of the country. The Zonal regime is linked with below-normal rainfall in the north and east, and above-normal temperatures in the south. This regime is less common in summer.

The 'Blocking' Kidson regime (mostly on the bottom row of Figure 3, types HE, NE, HSE, HW, R) is characterised by pressure highs lying to the south and east, and is linked with a southwest-northeast contrast in rainfall (below normal in SW, above normal in NE) and above-normal temperatures, except on the east coast of both islands. Blocking regimes are more frequent in summer and autumn.

Indices are presented here for the 12 types (Figure 4) as well as the 3 regimes (Figure 5).

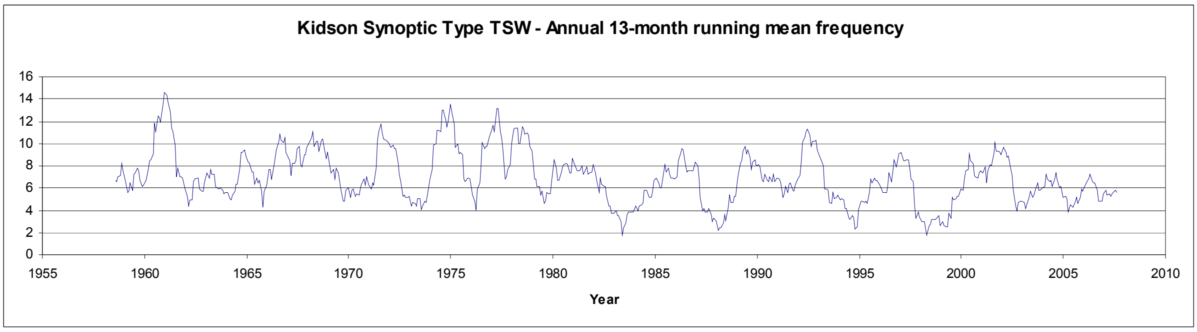
Trends/cycles and relevance to fisheries

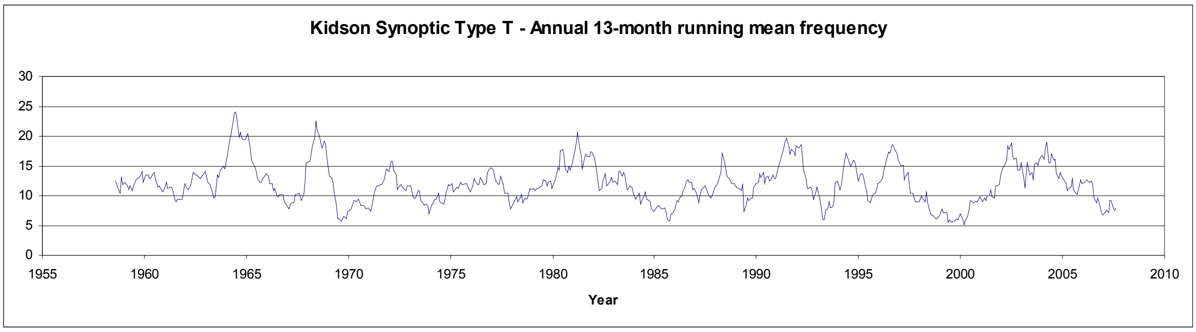
On monthly and annual scales the 12 weather-type indices show considerable variability. The occurrence of the different types is weakly modulated by large-scale conditions defined by ENSO and the IPO. For example, El Niño events and the positive phase of the IPO tend to favour more of the Zonal group of types and somewhat less of the Blocking group. During the positive phase of the IPO (1977–2000), the frequency of TSW and NE types was less on average and less variable than previously, whereas the frequency of W and HNW types increased and HW was less variable. Strongest correlations of Kidson regimes with each other (Table 3) are between Blocking and Trough (-0.57) and Blocking and Zonal (-0.56). Correlations between 3-month averages of the SOI and Kidson regimes are weaker; the Zonal and Blocking regime frequencies were around -0.26 and +0.24, respectively (Z and M indices are explained and discussed in Section 3.2 below). Studies attempting to link fisheries with Kidson weather types or regimes are listed in Table 1. Kidson weather types (e.g., SW, HSE, HNW) have been found to be correlated with gemfish, hoki, rock lobster, and southern blue whiting indices; Kidson regimes (Trough, Blocking and Zonal) with hake, hoki, red cod, red gurnard, rock lobster, school shark and southern blue whiting indices (Table 1).

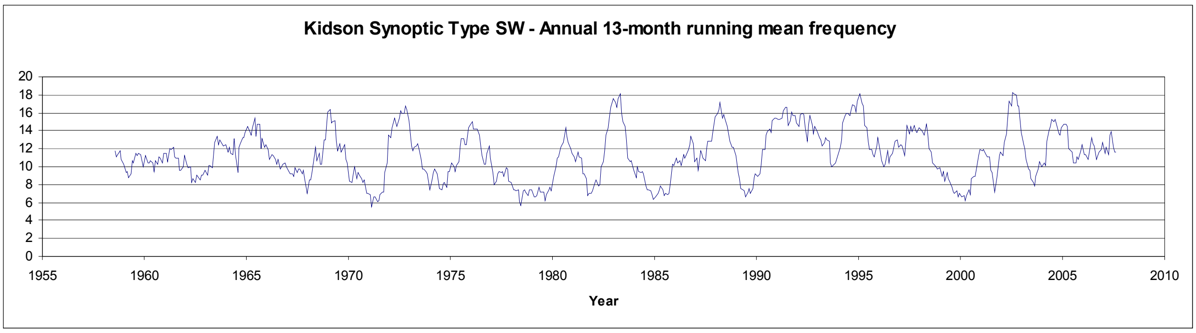
Table 3: Correlations between 3-month averages of the SOI, the 3 Kidson regimes and sets of 3 Trenberth indices (*see* Section 3.2).

	SOI	Trough	Zonal	Blocking	Z1	Z2	M1
SOI	1.0000	-0.0093	-0.2588	0.2372	-0.2556	-0.1721	-0.3335
Trough	-0.0093	1.0000	-0.3673	-0.5682	0.1964	-0.2871	0.2498
Zonal	-0.2588	-0.3673	1.0000	-0.5567	0.3976	0.6609	0.1499
Blocking	0.2372	-0.5682	-0.5567	1.0000	-0.5272	-0.3283	-0.3557
Z1	-0.2556	0.1964	0.3976	-0.5272	1.0000	0.5136	0.1996
Z2	-0.1721	-0.2871	0.6609	-0.3283	0.5136	1.0000	0.1931
M1	-0.3335	0.2498	0.1499	-0.3557	0.1996	0.1931	1.0000

The three regimes have a seasonal pattern, with reduced frequency of the Zonal regime and greater frequency of the Blocking regime over summer. The mean persistence of any regime tends to be a day or two, but individual regimes may dominate the weather for 2–4 weeks.







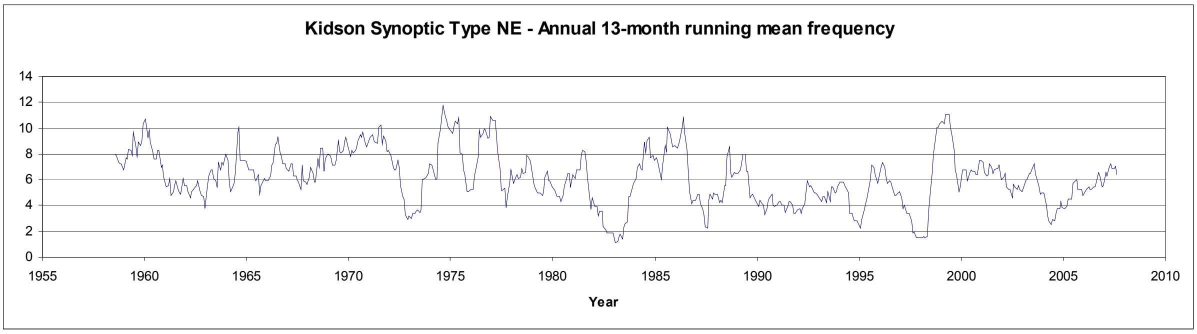
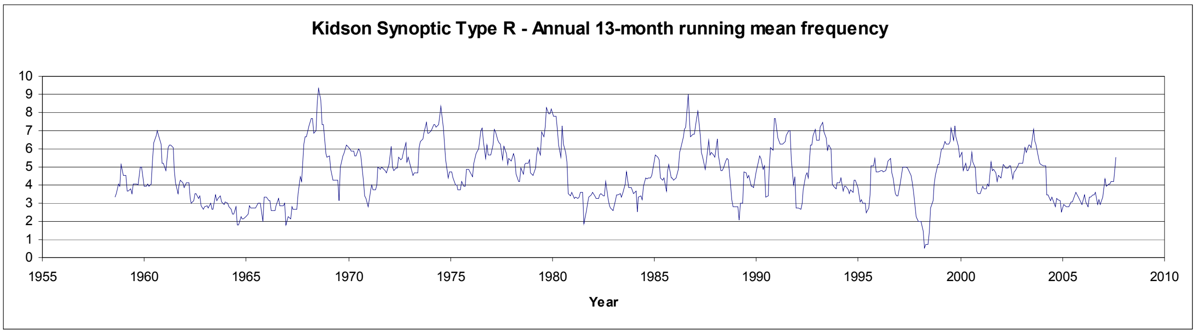
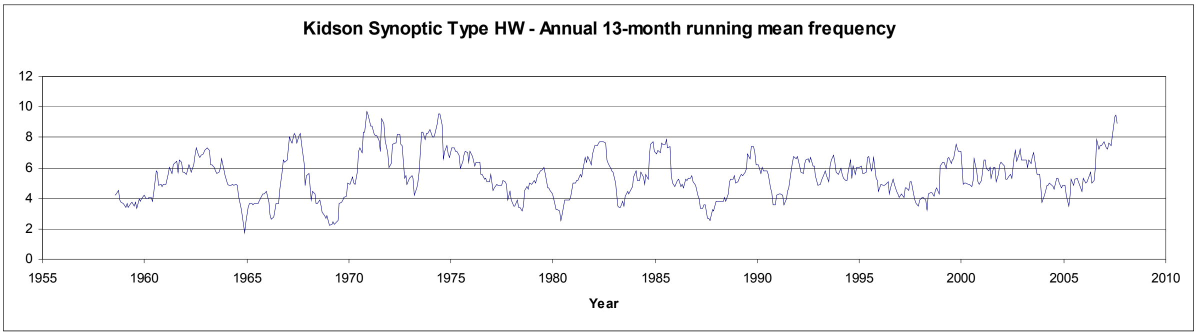
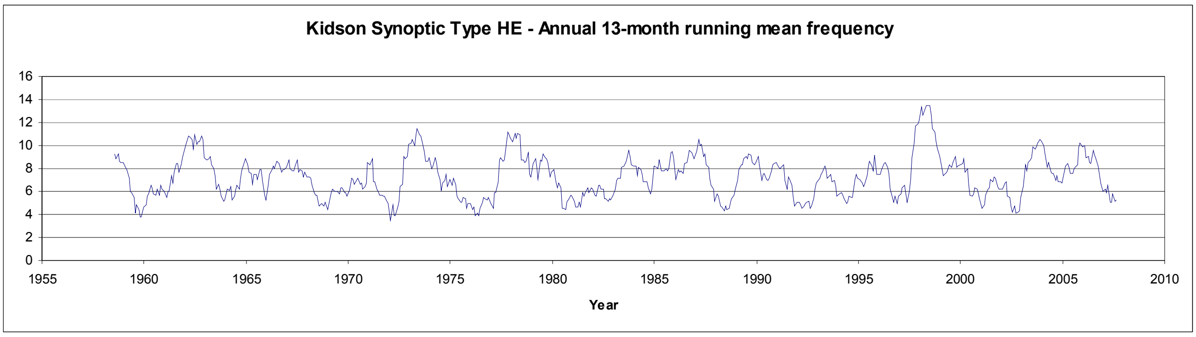


Figure 4: 13-monthly running mean frequencies for the 12 Kidson weather types.







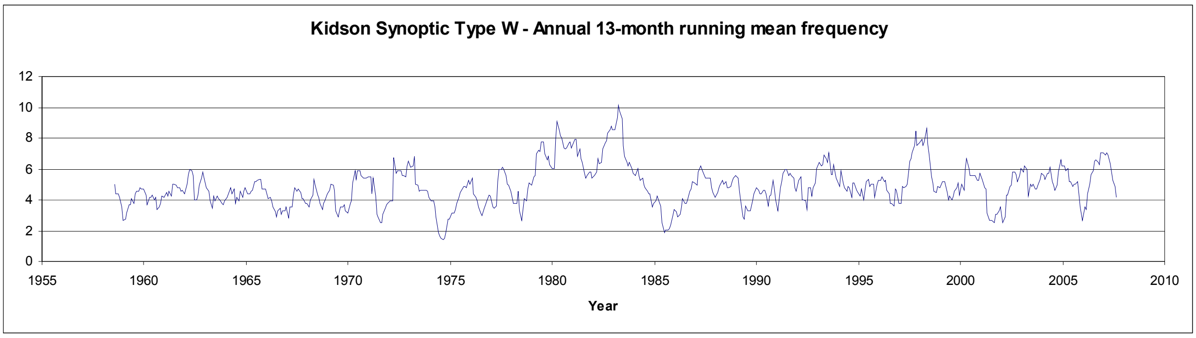
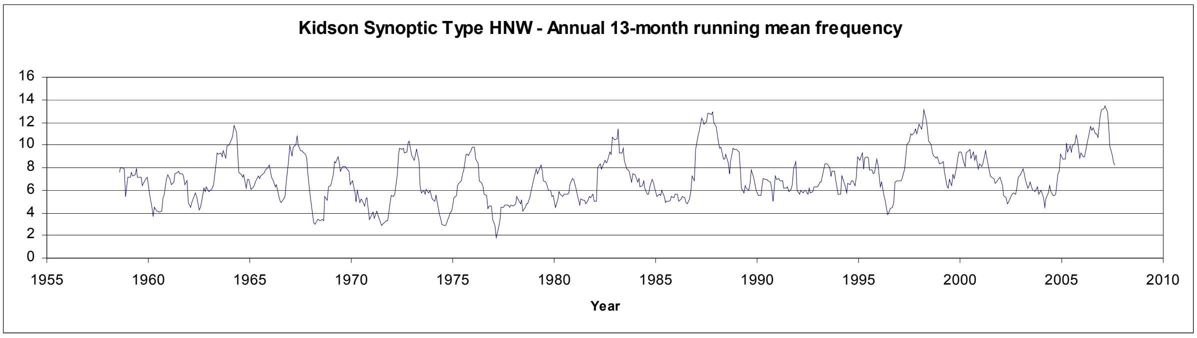
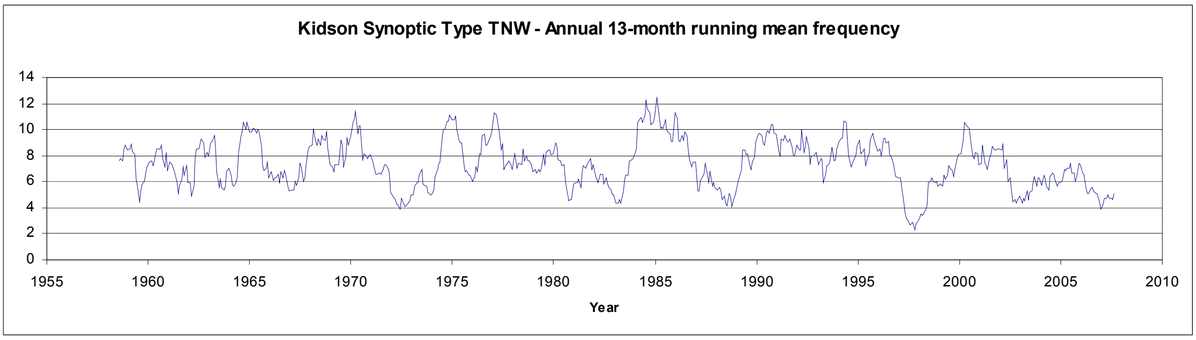
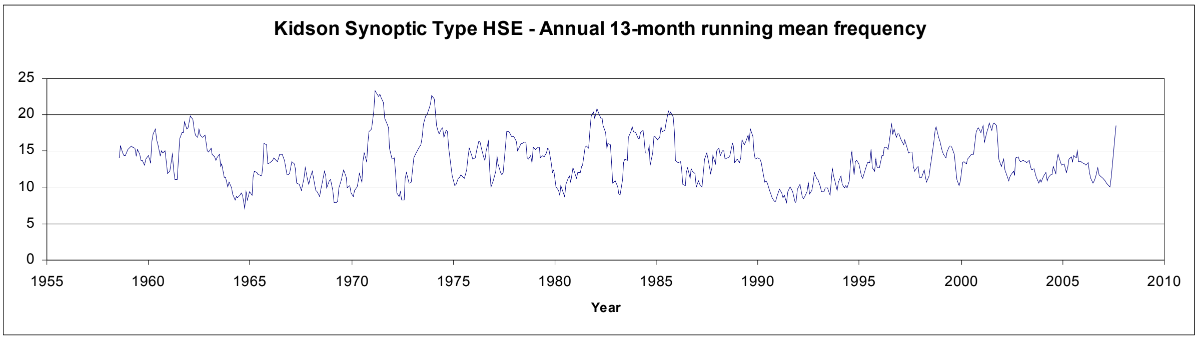


Figure 4 *continued*: Monthly and 13-monthly running mean frequencies for the 12 Kidson weather types.







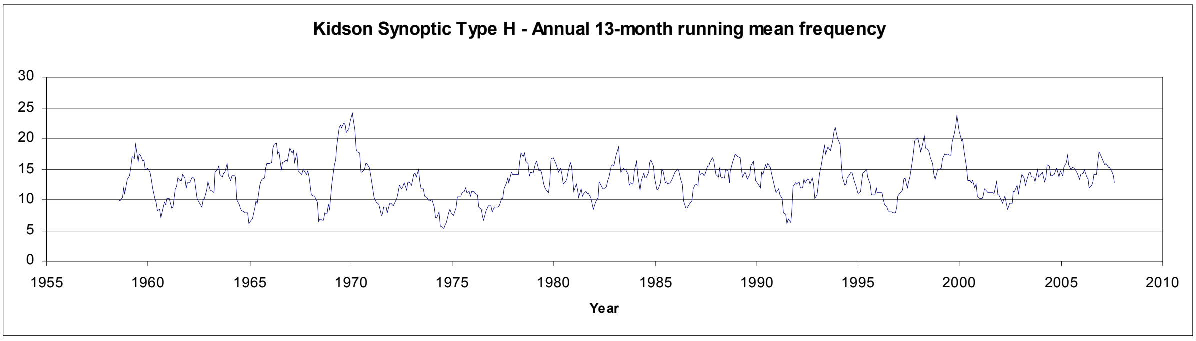


Figure 4 *continued*: Monthly and 13-monthly running mean frequencies for the 12 Kidson weather types.

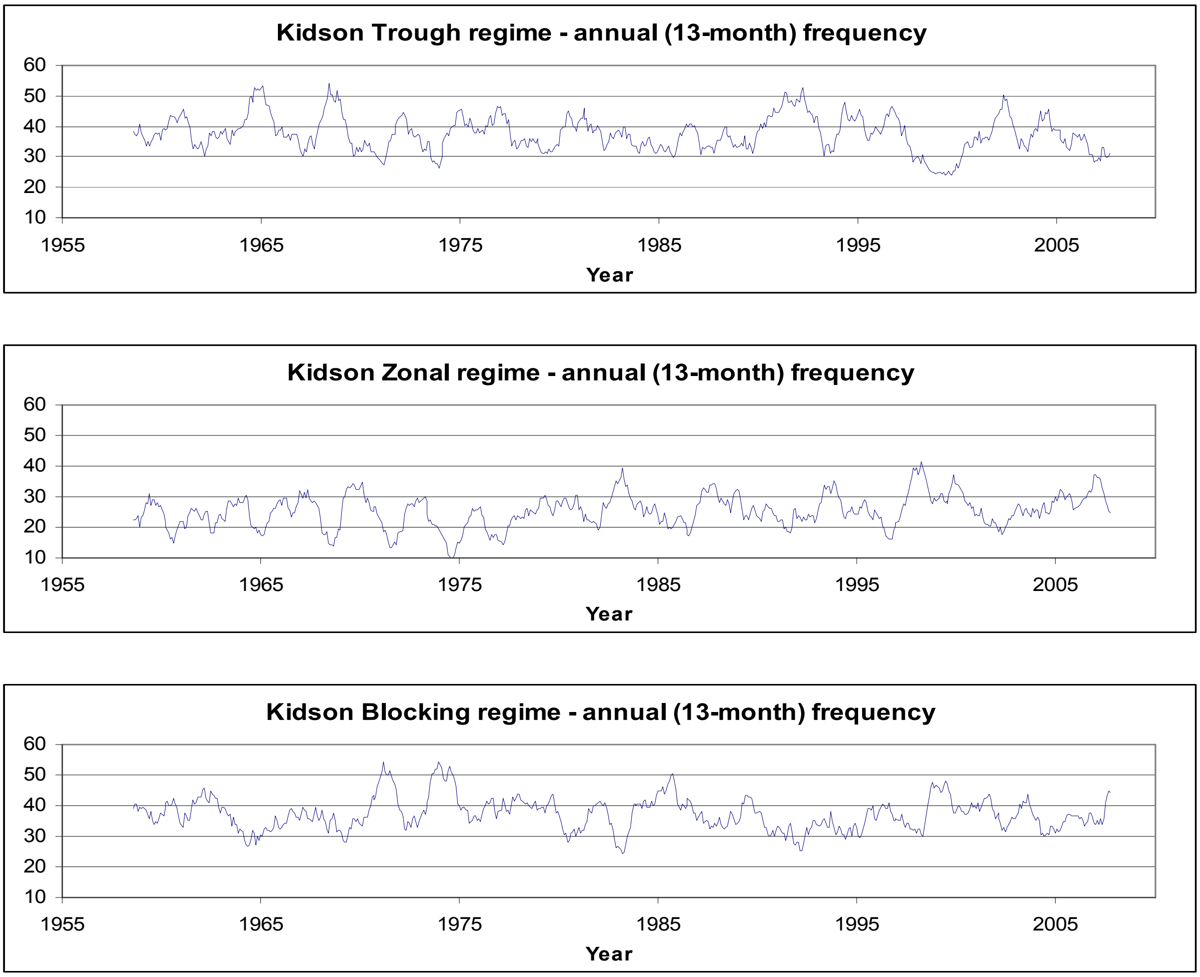


Figure 5: 13-monthly running mean frequencies for the three Kidson weather regimes.

3.3.2 Mean sea-level pressure indices – New Zealand

The 'Trenberth' indices (Trenberth 1976) describe monthly mean differences in mean sea-level pressure between several climate stations in the New Zealand region (in the same way that the SOI described above is an index of mean sea level pressure differences between the east and west Pacific). Pressure differences are directly related to wind speed (perpendicular to the orientation of the pressure difference), hence the Trenberth indices encapsulate monthly mean wind flows over New Zealand. As such, they are well correlated with some of the monthly 'Kidson' weather type and regime frequencies, which also capture wind flows and pressure patterns around New Zealand.

The Trenberth indices refer to specific areas of New Zealand, and are just differences in mean sea level pressure between the sites listed (Table 4). The pressure difference between two points is a direct proxy for the average strength of the wind perpendicular to that pressure difference, in the region between the points. Some of the 13 Trenberth indices are closely correlated with each other (see Dunn et al. 2009a) so a subset of five key indices are presented (indicated in bold in Table 4). Of those presented, the Z1 index is negatively correlated with the Blocking regime and the Z2 index is positively correlated with the Trough regime.

Zonal (westerly wind) anomaly over North Island/South Island/New Zealand/Campbell Plateau

The 'Z' indices are for Zonal (i.e., westerly) wind, as they are mostly north-south differences. The Z1, Z3, and Z4 indices tend to be correlated so only Z1 and Z2 are presented.

- Z1 is the monthly mean sea level pressure difference of Auckland minus Christchurch and measures (approximately) the strength of the westerly wind over the region of New Zealand between Auckland and Christchurch – i.e., the northern half of the EEZ.

- Z2 is the monthly mean sea level pressure difference of Christchurch and Campbell and measures (approximately) the strength of the westerly wind over the region of Christchurch and the Campbell Plateau – i.e., the southern half of the EEZ. This is a lot clearer and should maybe be moved up?

Meridional (southerly wind) anomaly over New Zealand

The 'M' indices are for Meridional (i.e., southerly) wind as they are mostly east-west differences. The M1 and M3 indices tend to be correlated so only M2 and M3 are presented.

- M2 is the monthly mean sea level pressure difference of Hokitika and Chatham and measures (approximately) the strength of the southerly wind over the region of the Chatham Rise – i.e., the eastern part of the EEZ.

- M3 is the monthly mean sea level pressure difference of Hobart and Hokitika and measures (approximately) the strength of the southerly wind over the region of the Tasman – i.e., the western part of the EEZ.

Northwest-southeast and southwest-northeast wind anomalies over New Zealand

The 'MZ' indices measure winds in the northwest-southeast and southwest-northeast directions. The Z1, MZ2, MZ3, and MZ4 indices tend to be correlated so only MZ1 is presented. (Note that the MZ3 index correlated with the SOI but is defined locally over New Zealand rather than in the Tropics).

- MZ1 is the monthly mean sea level pressure difference of Gisborne and Hokitika and measures (approximately) the strength of the northwest-southeast winds over the region of central New Zealand.

Indices are normalised to be unit standard deviation departures from a mean of zero and presented for the period January 1943–December 2007 in Figure 6, as annual 13-month running means. Note: 1943 was chosen as the start date as not all series go back beyond then.

Table 4: Trenberth indices (indices in bold are presented in this report).

Index	Sites	Correlation >0.7 (Dunn et al. 2009a)
Z1	**Auckland – Christchurch**	Z3, Z4, ZN, ZS, MZ2, MZ4
Z2	**Christchurch – Campbell**	ZS
Z3	Auckland – Invercargill	Z1
Z4	Raoul – Chatham	Z1
M1	Hobart – Chatham	M3
M2	**Hokitika – Chatham**	Z4, MZ3
M3	**Hobart – Hokitika**	M1
MZ1	**Gisborne – Hokitika**	
MZ2	Gisborne – Invercargill	Z1, ZS
MZ3	New Plymouth – Chatham	Z1, Z4, M2, ZN, MZ4
MZ4	Auckland – New Plymouth	Z1, Z4, ZN, MZ3
ZN	Auckland – Kelburn	Z1, Z3, Z4, MZ3, MZ4
ZS	Kelburn – Invercargill	Z1, Z2, Z3, MZ2

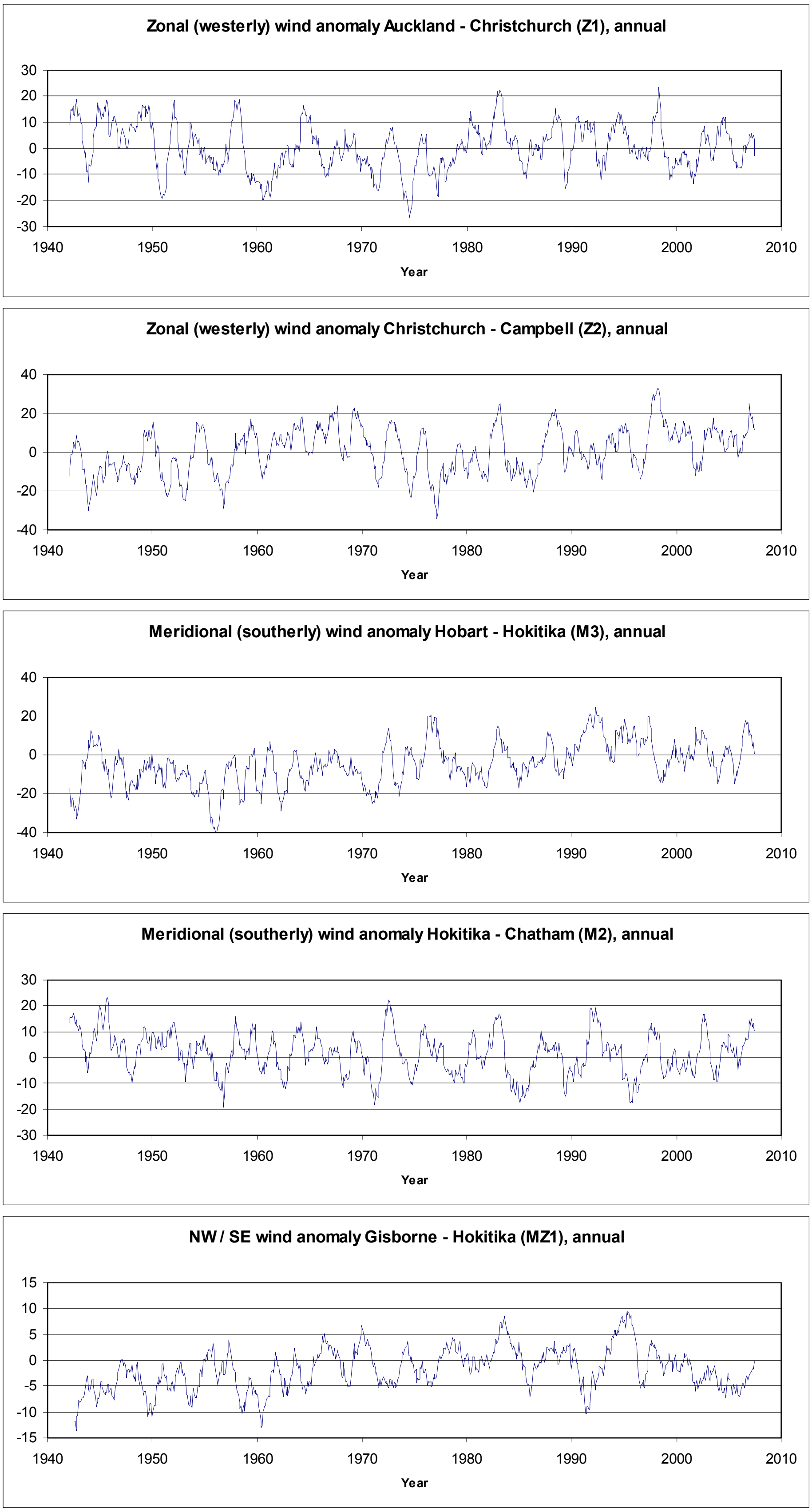


Figure 6 Trenberth wind anomalies over New Zealand – annual 13-month running averages.

Trends/cycles and relevance to fisheries

The weather types and Trenberth indices both describe New Zealand-local climate variations. A significant fraction of the variability is associated with weather events and is hence unpredictable, or random, on monthly and longer time scales. However, large-scale climate signals do modulate surface climate over New Zealand. As indicated above, the ENSO cycle in the tropical Pacific has a strong influence on New Zealand: when the SOI is strongly positive, New Zealand tends to experience reduced westerly winds and milder, more settled, anticyclonic weather; when the SOI is strongly negative, New Zealand tends to experience increased westerly winds and cooler, less settled weather.

General trends apparent in the Trenberth indices are a period of more frequent zonal westerly winds across the main part of the country in the periods 1942–52 and 1980–2000, the latter period is consistent with the pattern in El Niño events. Further south, down to Campbell Island, zonal westerlies also appear to have been more frequent since 1980. Southerly wind anomalies appear to show some correlation with the IPO: across the country and Chatham Rise the periodicity in fluctuations from positive to negative becomes more regular at every 2–3 years during the 1970–2000 period; over the Tasman Sea, the southerlies become more frequent during the same period. Trenberth indices (e.g., M1, Z4) have been found to be correlated with hoki and red gurnard biomass indices (Table 1).

3.4 New Zealand average air temperature

Annual temperature anomalies are presented from 1906 to 2005 for New Zealand (Figure 7a), the North and South Islands (Figures 7b, 7c), and 8 of 21 possible individual sites (Figures 7d). Data are available from the mid 1850s for some of these areas but are more comprehensive from the early 1900s. Individual sites were selected on the basis of length of the data series, coastal location, and north, south, east, and west for each Island.

Trends/cycles and relevance to fisheries

During the last century, the overall trend for all areas and New Zealand as a whole has been of increasing temperature anomalies. However, until the early 1950s the trend was relatively flat. Since the mid 1950s, the average anomaly in New Zealand air temperatures has been 0.55 higher than in the earlier period and is showing a slightly increasing trend. This is mirrored in the indices from individual sites, with New Plymouth showing the greatest differential between the two periods (0.79) and Appleby (Nelson) showing the least (0.40). This increasing trend is likely to have been moderated by the positive phase of the IPO, from the late 1970s to the late 1990s. The increases in New Zealand are consistent with an increase in air temperatures in the Australasian region of 0.5 to 0.9 °C since the beginning of the century (Salinger et al. 1996) and the global mean trend of +0.7 °C from 1906 to 2005 (Trenberth et al. 2007).

Smoothed air temperatures correlate well with sea surface temperatures (SST) in terms of interannual and seasonal variability in the New Zealand region (Folland & Salinger 1995); the overall SST increase in the New Zealand region between 1900 and 1980 is 0.8 °C (Wratt et al. 2007). Globally, recent warming of SSTs is strongly evident at all latitudes over each of the oceans (Trenberth et al. 2007). Where SST data are available, these tend to be used in preference for fisheries correlative studies. However, the SST series can be short and air temperatures have been used as a proxy for SST. For example, Gilbert & Taylor (2001) found that snapper recruitment had a positive relationship with spring and summer air temperatures off the northwest of the South Island (SNA 7) and lower east of the North Island (SNA 2) and recommended using temperature predictors for future year class strength in snapper population models, rather than assuming average recruitment.

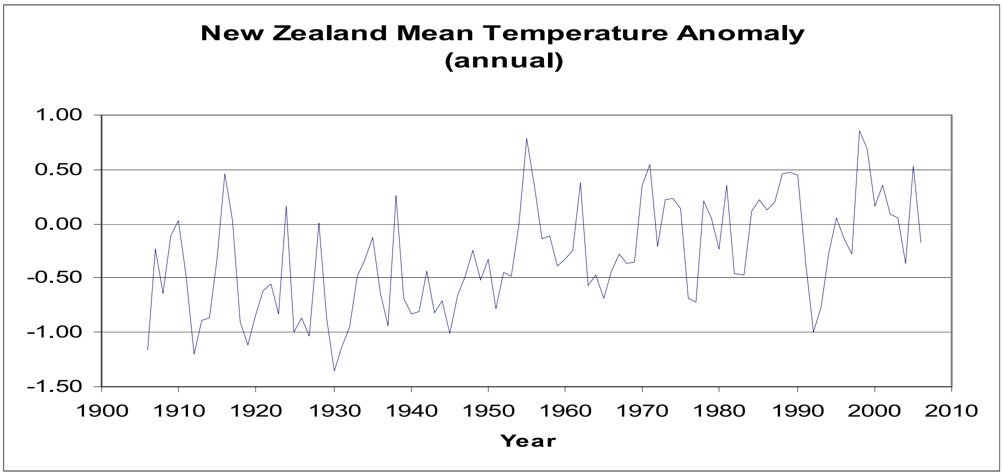


Figure 7a: New Zealand mean temperature anomaly (annual).

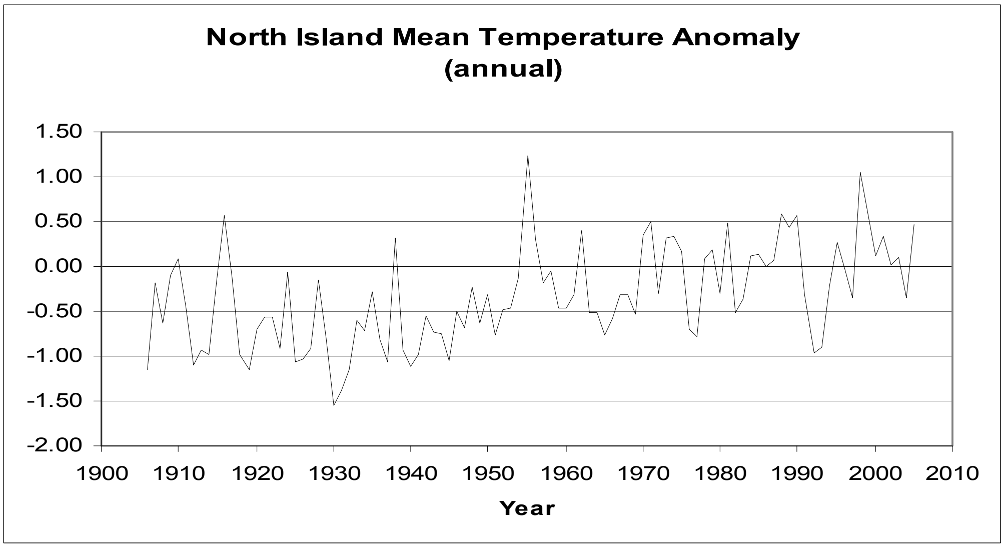


Figure 7b: North Island (11 sites) mean temperature anomaly (annual).

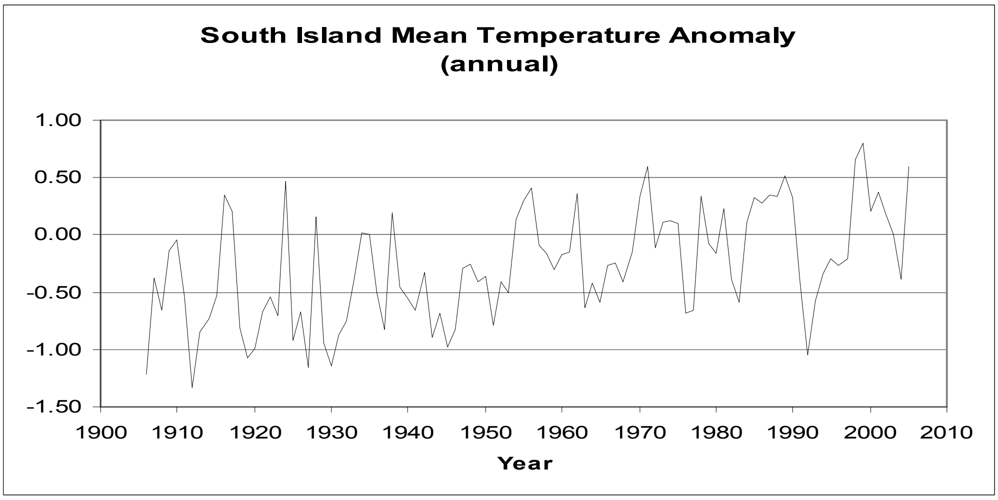


Figure 7c: South Island (10 sites) mean temperature anomaly (annual).

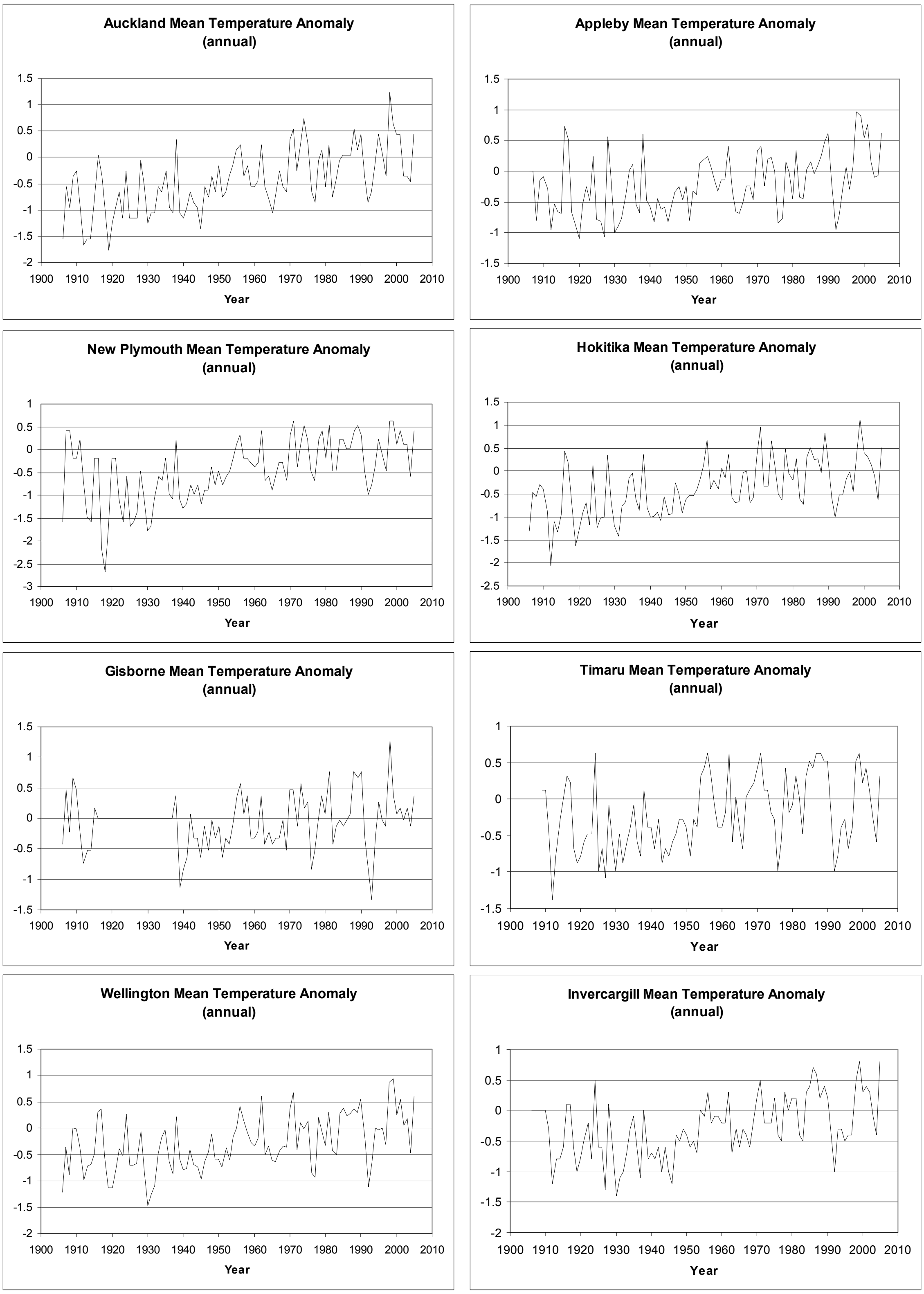


Figure 7d: North (left panel) and South Island (right panel) coastal sites mean temperature anomalies (annual).

Ocean variables

Oceanographic indices or data summaries presented here include sea surface temperature (SST) from two sources (coastal monitoring stations and satellites), upwelling and ocean colour (derived from satellite SST data), temperature (at depth from expendable bathythermographs), and reviews of the state of knowledge of currents and acidification. Oceanographic indices are available on much shorter time scales than climatic indices, mostly for only the last two decades.

3.5 Coastal SST measurements

There are 11 sites at which coastal sea-surface temperature (SST) data have been recorded over an extended period. Nine of these are NIWA monitoring stations that have recorded temperatures over that last 20–30 years, just below low tide in 1–2 m of water. Many of these have been automated in recent years and the frequency of data recording has changed from about daily to several hours. The other two are university marine stations that have the longest records of coastal SST in New Zealand; Portobello, in Otago Harbour, since 1953, and Leigh, north of Auckland, since 1967 (data courtesy of Portobello Marine Laboratory, University of Otago and Leigh Marine Laboratory, University of Auckland). The locations of these monitoring sites are shown in Figure 8. Monthly averages (where there are more than five observations) and annual running (i.e., 12 monthly) means records are presented in Figure 9. Collection dates for the data series and a brief description of the data collection are shown in Table 5:

Table 5: Coastal SST monitoring sites and periods sampled.

Site	Date
Ahipara Bay, Northland (NIWA)	1991 – 2007
Leigh Marine Station	1967 –
Tauranga – Motoriki Island (NIWA)	1990 –
Napier (NIWA)	1977 – 2005
New Plymouth (NIWA)	1977 –
Wellington – Evans Bay (NIWA)	1981 –
Wellington – Lyall Bay (NIWA)	1982 – 2006
Lyttelton – Little Pidgeon Bay (NIWA)	1978 –
Jackson Bay (NIWA)	1991 –
Portobello Marine Station	1953 –
Bluff (NIWA)	1978 – 1986, 1991 –1999

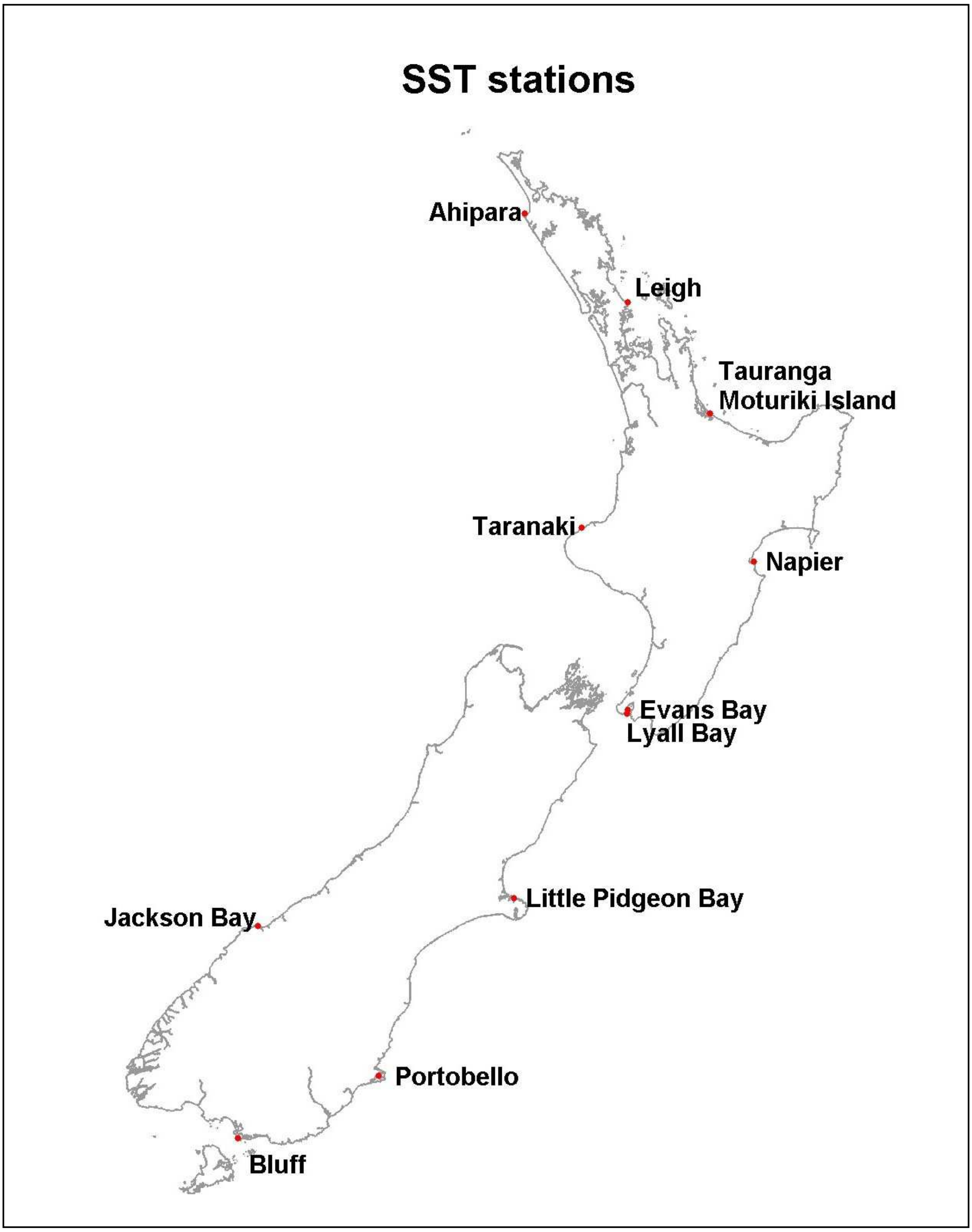


Figure 8: Location of coastal SST monitoring sites.

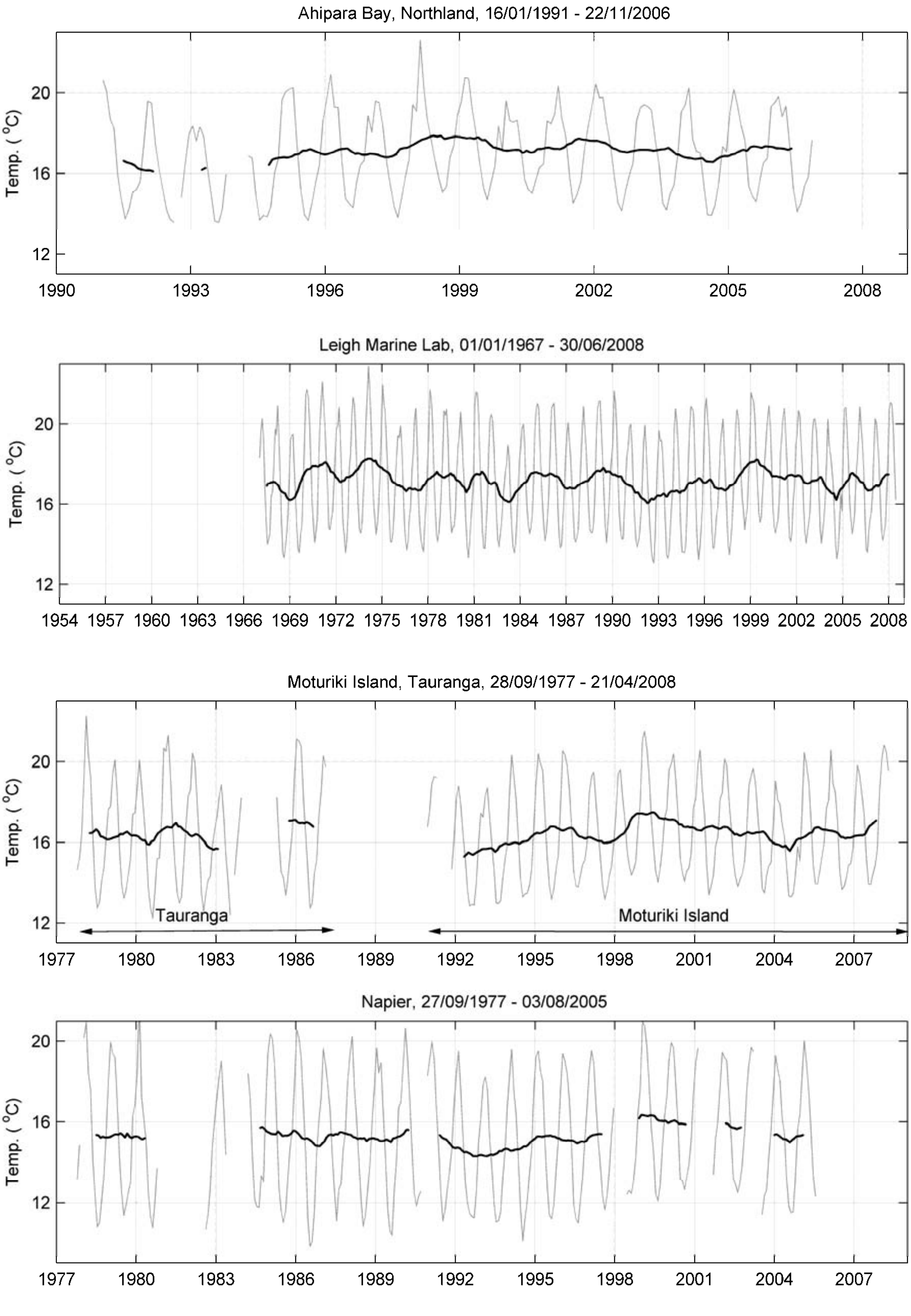


Figure 9: SST series from 11 coastal monitoring sites.

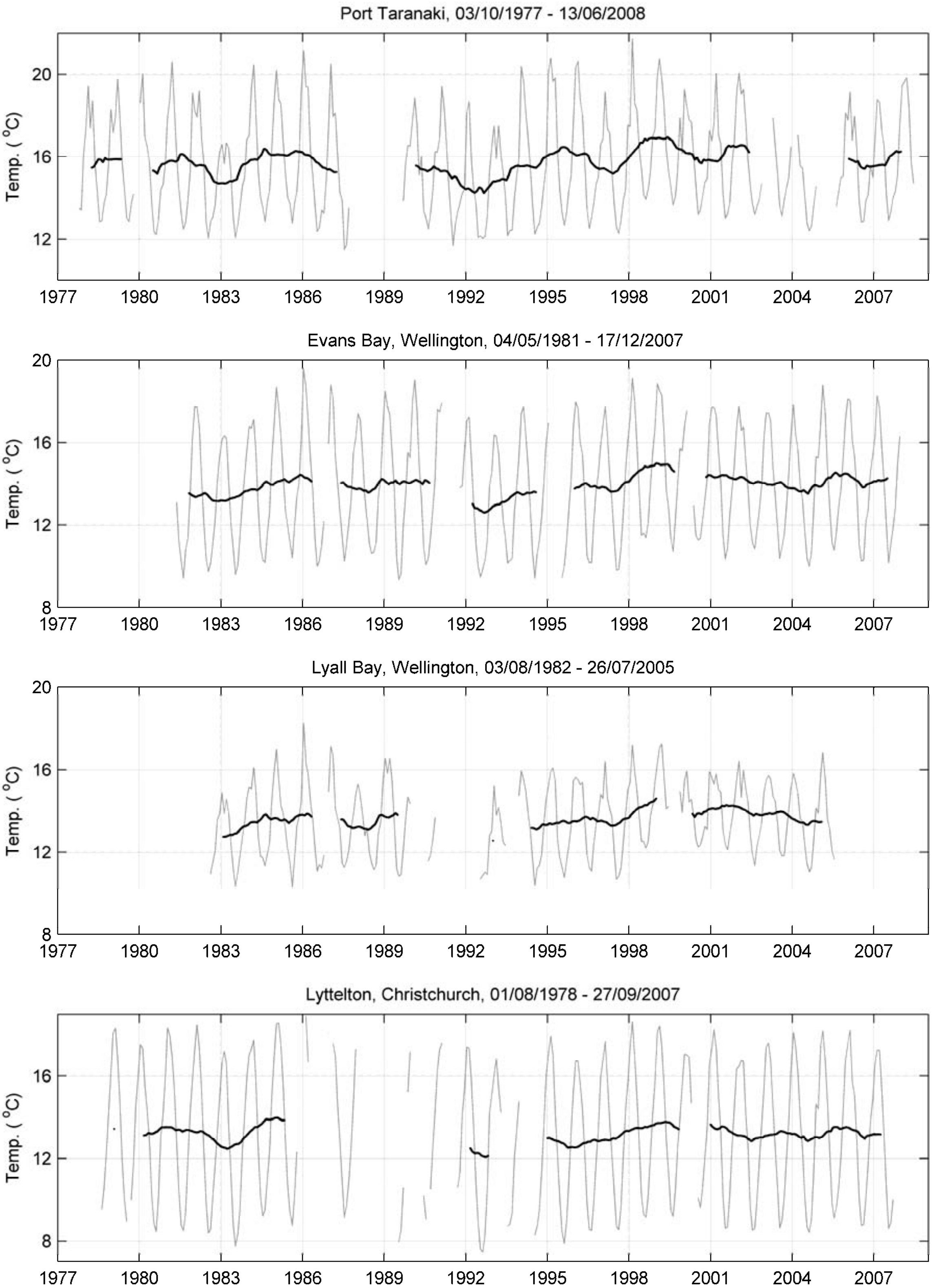


Figure 9 *continued*: SST series from 11 coastal monitoring sites.

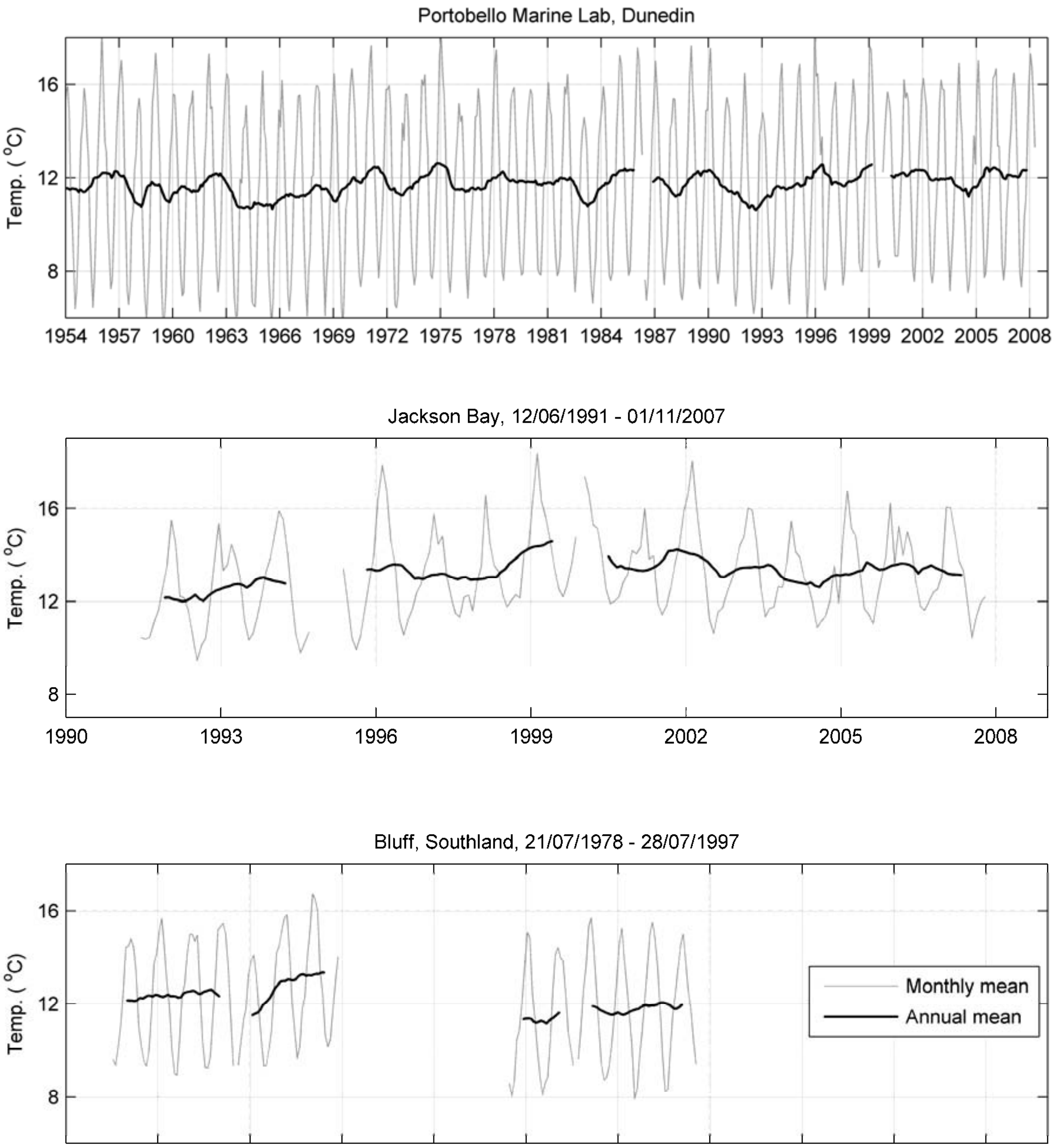


Figure 9 *continued*: SST series from 11 coastal monitoring sites.

Trends/cycles and relevance to fisheries

Monthly temperature values have been used to calculate a running annual mean, which eliminates seasonal and other shorter period variations. Most series are too short (or broken) to show much more than interannual fluctuations. The 1998−1999 period appears warmer than average in most series; longer series also have a peak warm [period in the early 1970s. Stanton (2001) observed that the two longest time series, Leigh and Portobello, even though at opposite ends of the country, showed similar interannual fluctuations, although the amount of variation was slightly greater in the north, up to 2 °C.

Greig et al. (1998) compared SST observations from 16 coastal sites around New Zealand with some corresponding air temperatures. They found that day-to-day variations in SST showed weak periodicity over an 8–16 day range. Air temperatures were generally cooler than SST and short-term fluctuations had 3–4 times the standard deviation of the SSTs. Seasonal SST variations were described and coastal SSTs were compared with offshore SST data. Coastal SSTs had a greater annual range than offshore and were generally warmer in the summer and cooler in the winter, except at Farewell Spit, where the coastal SSTs were always cooler than offshore SSTs which supported the view that upwelling is persistent in the Cape Farewell region.

Greig et al. (1998) and Stanton (2001) found that interannual variations in SST were correlated with the SOI; El Nino events were accompanied by lowered SSTs throughout New Zealand's coastal waters (e.g., the 1982–83 El Niño, and the prolonged El Niño conditions in the early 1990s). However, Stanton (2001) also noted that the very strong 1997–98 El Niño was not associated with cooling conditions, demonstrating that we still have limited understanding of the connection between ENSO and sea surface temperatures. This is illustrated by SOI and Leigh SST data shown in Figure 10; cross correlation analysis between the smoothed SST and SOI time series shows a coefficient of 0.62.

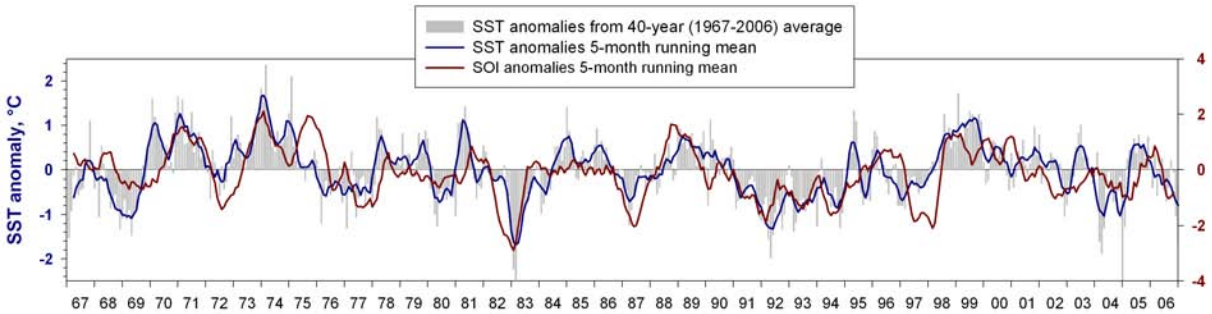


Figure 10: SOI and Leigh monthly SST anomalies.

Coastal SST data, particularly the longer time series from Leigh and Portobello, have been used in studies attempting to link processes in the marine environment with temperature. The clearest fisheries example of a link between coastal SST and fish recruitment and growth is for northern snapper, where relatively high recruitment and faster growth rates have been correlated with warmer conditions from the Leigh SST series (Francis 1993, 1994a).

3.6 Sea surface temperature (SST) monthly climatology and regional analyses (Base period: 1993–2007)

3.6.1 Introduction

Since January 1993, NIWA has archived all data received from NOAA series satellites. The Advanced Very High Resolution Radiometer (AVHRR) instrument on board these satellites senses radiation with a spatial resolution of the data at the surface of 1 km. In the infrared the AVHRR measures thermal radiation emitted by the Earth's surface, atmospheric water vapour, and clouds, while in the visible, it measures reflected (solar) radiation. These data may be used to retrieve estimates of sea surface temperature (SST) over cloud free regions. The data used in this analysis, the NIWA SST Archive (NSA), have been derived using a Bayesian cloud detection algorithm and non-linear SST retrieval algorithm, with each orbits data being remapped onto a Lambert Conformal map projection having 1 km resolution pixels. These data in turn have been temporally composited in order to estimate the monthly mean SST at each location on the map grid. Depending on the number of satellites available, and the cloud cover encountered, the SST at any point could be computed from

as many as 300 or more individual observations. For full details of the methods used, see Uddstrom & Oien (1999) and Uddstrom et al. (1999).
The monthly mean data have been used to estimate the annual mean and the amplitudes and phases of the first four harmonics of the seasonal cycle. Then, using these harmonic components, filtered estimates of monthly mean SSTs were computed, allowing the specification of monthly anomalies, regional averages of these anomalies, and the specification of the modes of variability through the calculation of seasonal and spatial anomaly Empirical Orthogonal Functions (EOFs). The following sections provide additional details.

Even at monthly time scales, the data may contain correlated 'noise' – perhaps resulting from cloud detection problems, or because of enhanced surface mixing resulting from severe weather. To reduce the impact of such noise sources, the 180 month series (1993–2007 inclusive) were expanded as a harmonic series at each location and time step.

The annual mean, and the amplitude of the first and second harmonics, and their phases are given in Figures 11a, 11b and 11c. Based on Figure 11b, the maximum summertime SST occurs around the end of February, and consequently the winter minimum will be in late August. The semi-annual cycle (Figure 11c) is much smaller than the annual cycle, and in subtropical waters (and south of the Chatham rise) first peaks in early February.

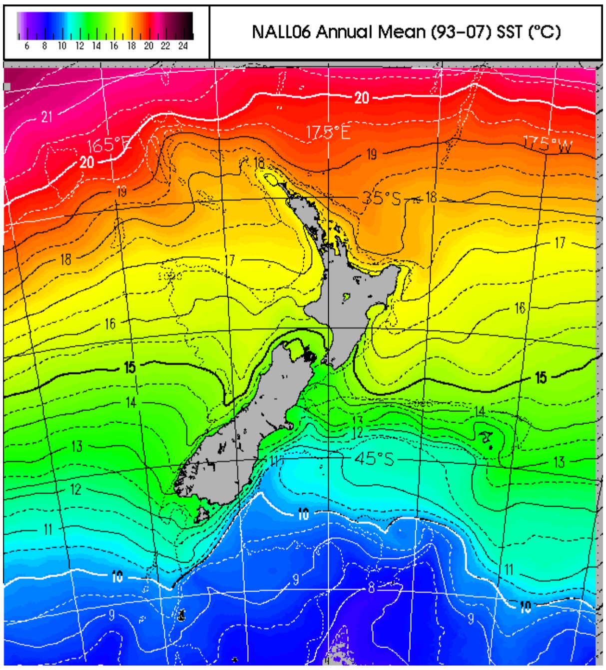


Figure 11a: Annual mean SST (Base period: 1993–2007).

Interpretation

The left hand panel is an estimate of the annual mean SST based on 1993 to 2007 satellite SST data, where the total sample size is of the order of 30 000 at each analysis point on a 5 × 5 km grid, which in turn is derived from 5 × 5 1 km resolution data points

The two panels below show the amplitude of the harmonic of the time series at each analysis grid point (colour), and the contours show the phase, the day of the year on which the annual or semi-annual cycle reaches its maximum value (1-January is day 1)

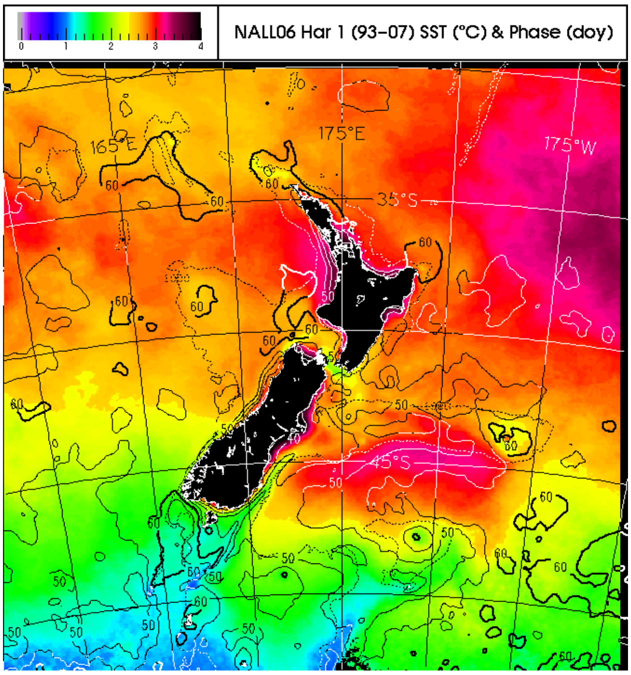


Figure 11b: First harmonic (annual cycle) and phase (in days from 1-January).

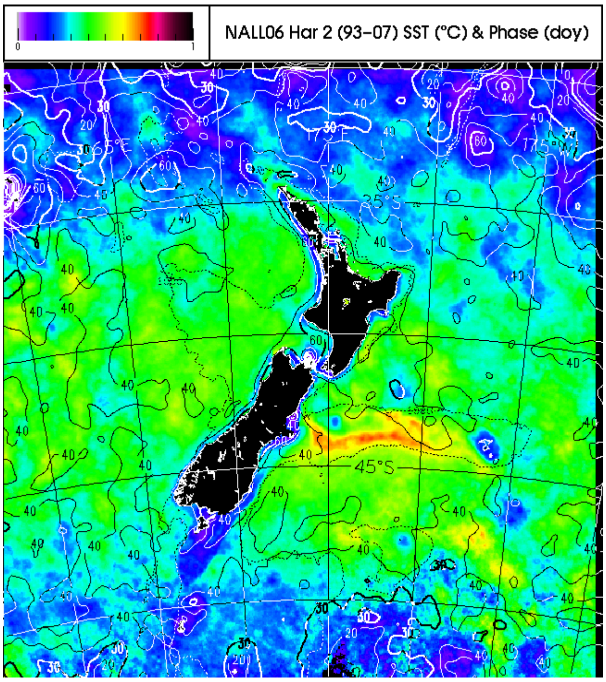


Figure 11c: Second harmonic (semi-annual cycle) and phase (in days from 1-January).

This analysis of climate and variability has previously been extended back to 1985 (Figure 12) at lower spatial resolution using NOAA Pathfinder data (Uddstrom 2003).

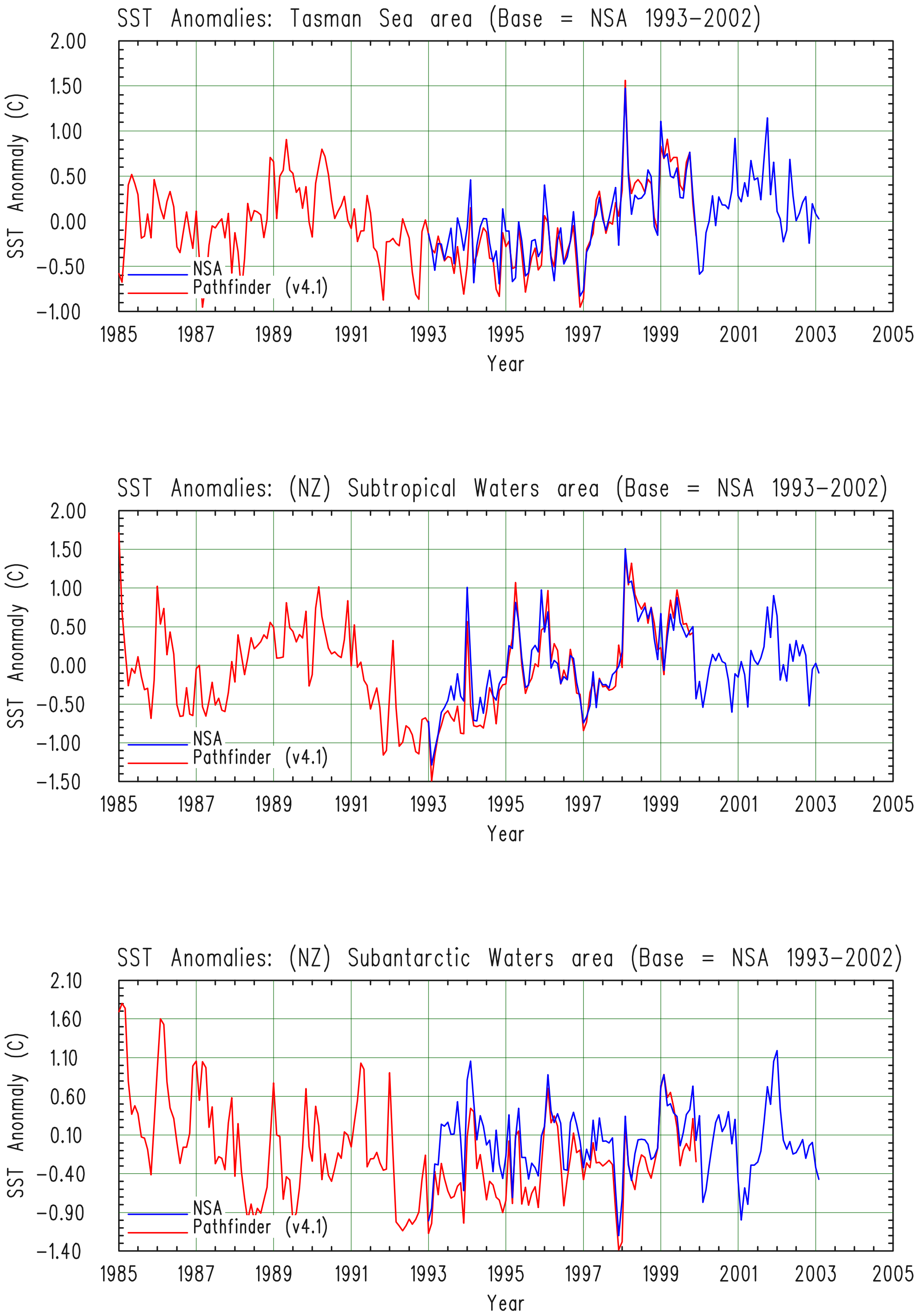


Figure 12: Extended time series (back to 1985), for the Tasman Sea (top), Subtropical waters north and east of New Zealand (middle) and SubAntarctic waters south of the Chatham Rise (lower panel). Domains are as in Figure 13, except that Tasman Sea includes TF and SubAntarctic includes ACC.

Estimates of the monthly mean SST climatology are given in Appendix 2, and have been generated from the annual mean and first four harmonic components. Given the observed monthly analyses, this climatology can then be used to estimate monthly anomalies. These are presented in Appendix 5 for all data from January 1993 till June 2008.

3.6.2 Regional Averages

A time series of the gross characteristics of watermasses in the region can be estimated by analysing the mean monthly anomaly (and its spatial standard deviation) over general areas associated with important oceanographic features. The mean provides general information about warming and cooling trends and cycles, while the standard deviation may be used to infer some dynamical aspects, e.g., when the mixed layer is nearly isothermal due to vertical mixing (e.g., in winter) the spatial standard deviation should be low, while in summer, stratification of the mixed layer means that the estimate of SST is may be more sensitive to weather system 'noise'.

The region was divided into five watermass classes; the Tasman Front (TF), Tasman Sea Subtropical Waters (TS-STW), Subtropical Waters (STW) east of New Zealand and north of the Chatham Rise, Sub-Antarctic Waters (SAW) south of the Chatham Rise, and west of the northward intrusion of the Antarctic Circumpolar Current (ACC), and the ACC (Figure 13).

The results of these analyses are shown in Figure 14a–g.

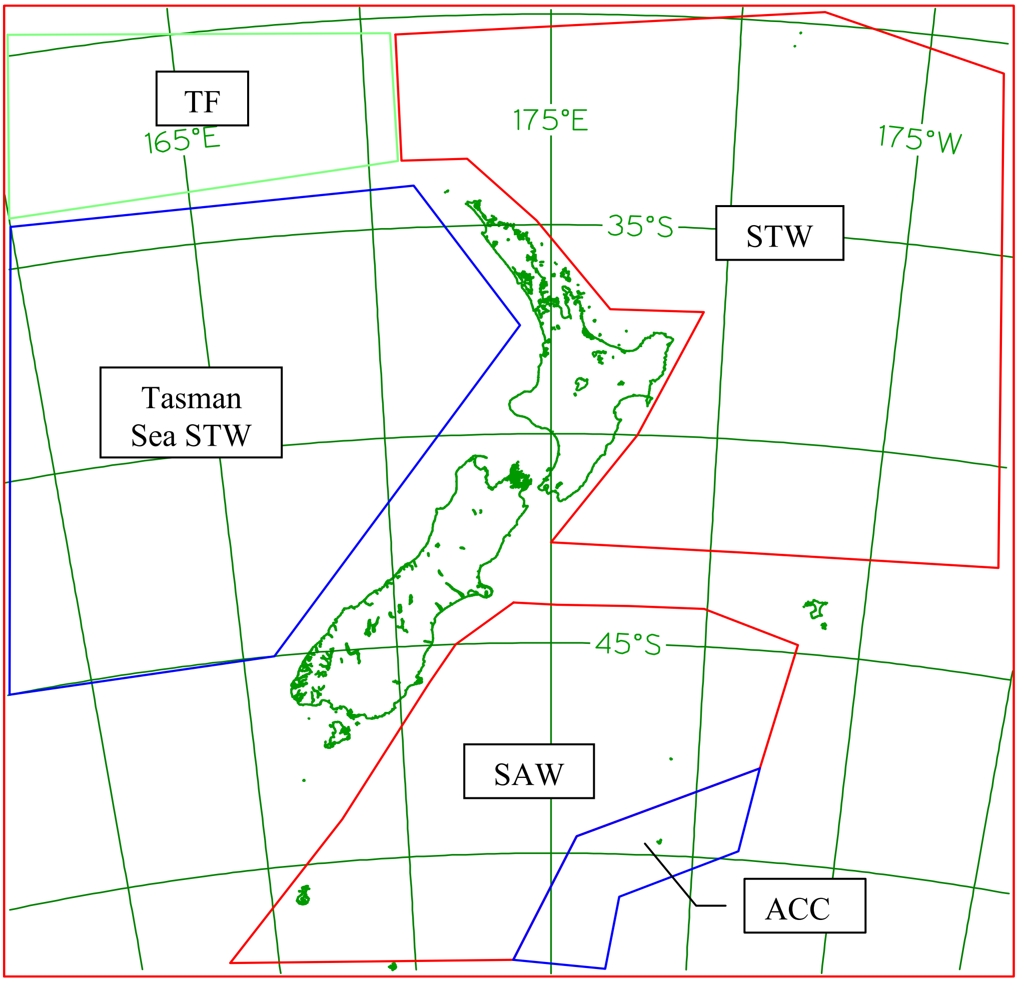


Figure 13: Watermass domains for SST Anomaly time series analysis.

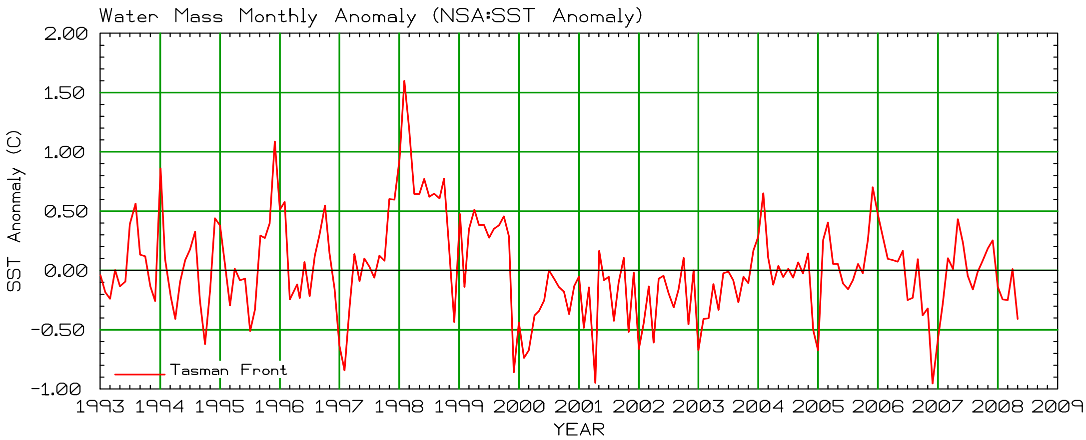


Figure 14a: Mean monthly SST Anomaly for the Tasman Front domain.

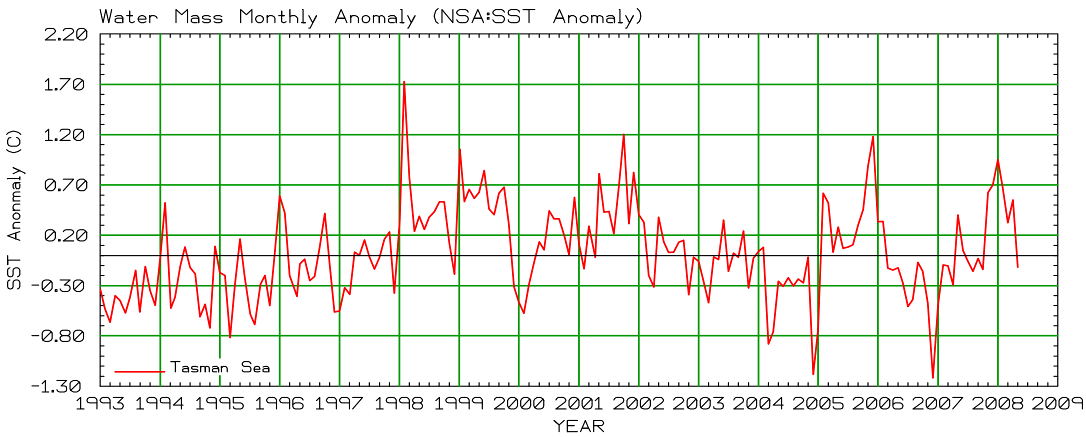


Figure 14b: Mean monthly SST Anomaly for the Tasman Sea Subtropical Waters domain.

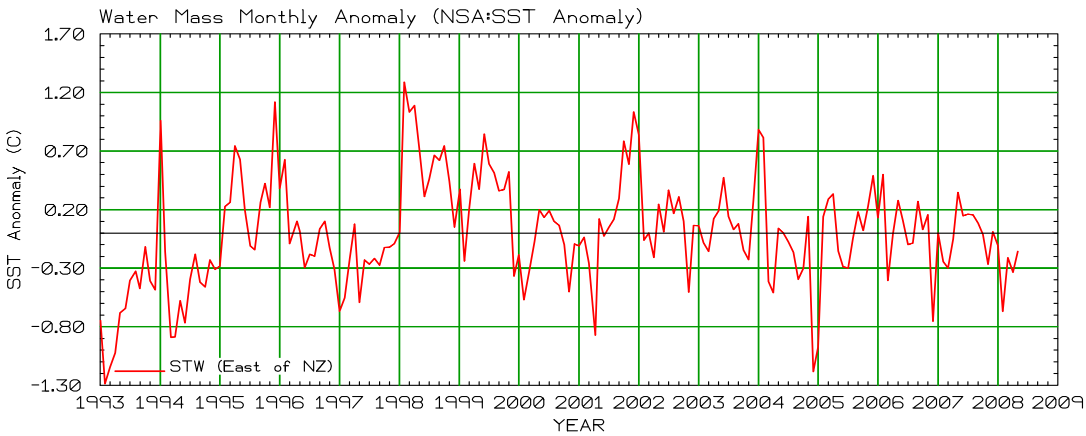


Figure 14c: Mean monthly SST Anomaly for Subtropical Waters east of the New Zealand domain.

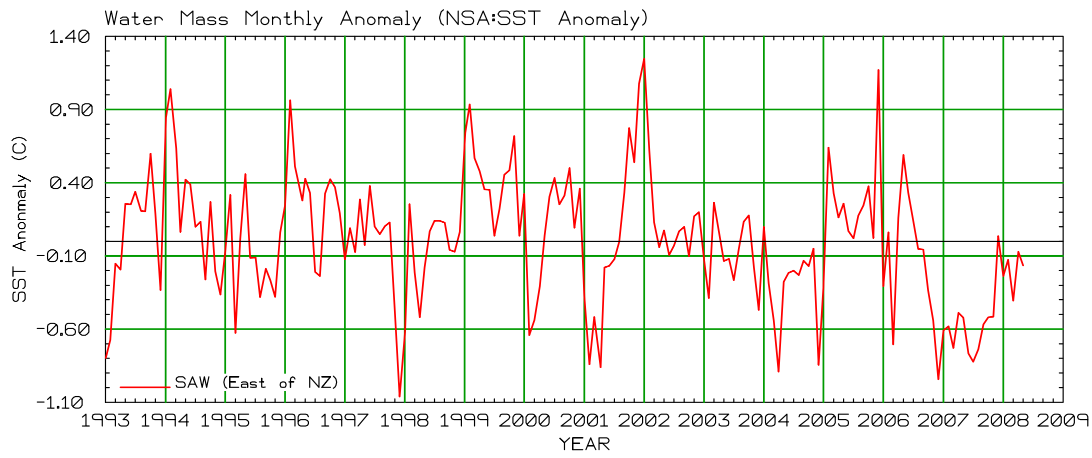


Figure 14d: Mean monthly SST Anomaly for the SubAntarctic Waters domain.

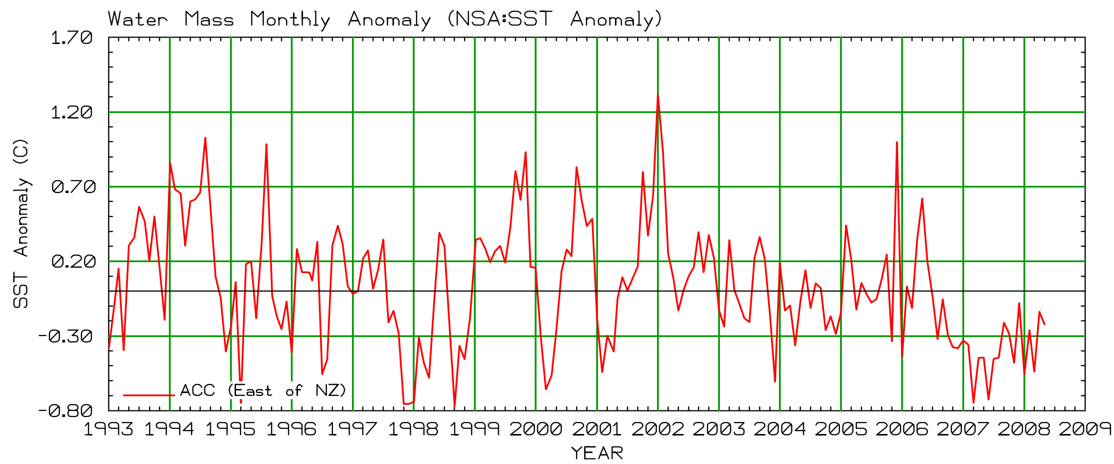


Figure 14e: Mean monthly SST Anomaly for the Antarctic Circumpolar Current Waters domain.

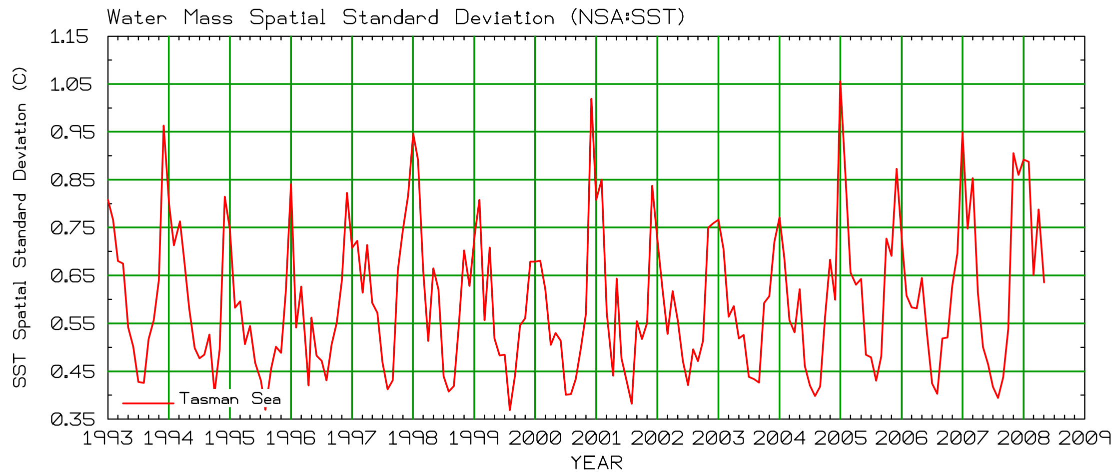


Figure 14f: Spatial Standard Deviation of the monthly SST Anomaly for the Tasman Sea Subtropical Waters domain.

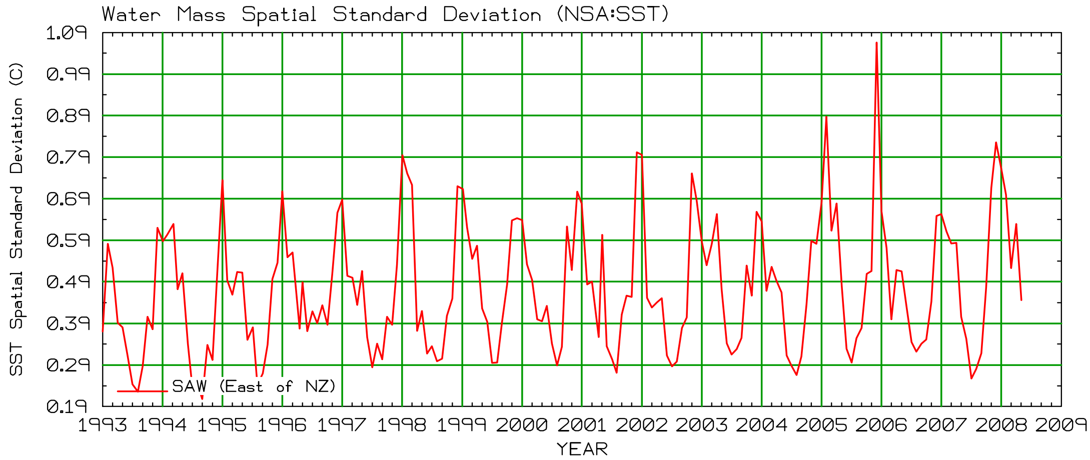


Figure 14g: Spatial Standard Deviation of the monthly SST Anomaly for the SubAntarctic Waters domain.

3.6.3 Empirical Orthogonal Function (EOF) analysis

EOF analyses (Preisendorfer 1988) were computed from both temporal and spatial anomalies. In the first instance the anomalies are defined to be

$$SST(x,t) - \overline{SST(x)},$$

representing departures from the annual mean. In contrast, spatial anomalies were computed by removing the spatial mean from each month's data, i.e.,

$$SST(x,t) - \overline{SST(x,t)}.$$

EOFs were calculated via singular value decomposition of the (time × space) anomaly data matrix, with missing data estimated by a weighted average of nearby values.

These analyses decompose the spatial variability in the SST data. The temporal variability of any EOF component is recovered from the dot product of the loading for that EOF and the data matrix. Varimax rotation (Richman 1986) was also applied to better identify physically realistic modes of SST variability. The sign of the EOF is arbitrary. The first EOF of each of these series is shown in Figure 15.

The results of these analyses for the first eight rotated EOFs are given in Appendix 3: Rotated Orthogonal Functions – Seasonal Anomaly and Appendix 4: Rotated Orthogonal Functions – Spatial Anomaly. The first EOF of each of these series is shown in Figures 15a and 15b.

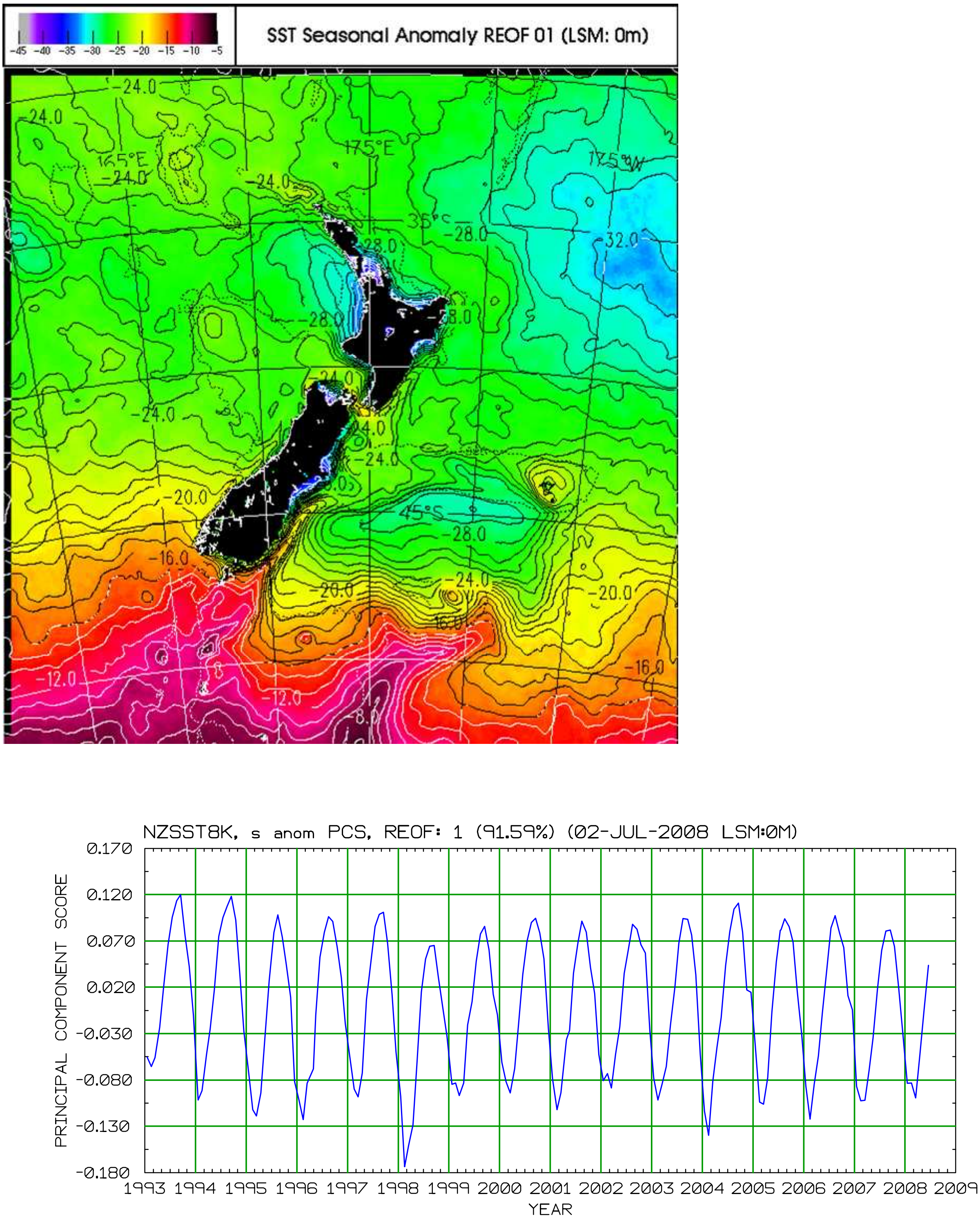
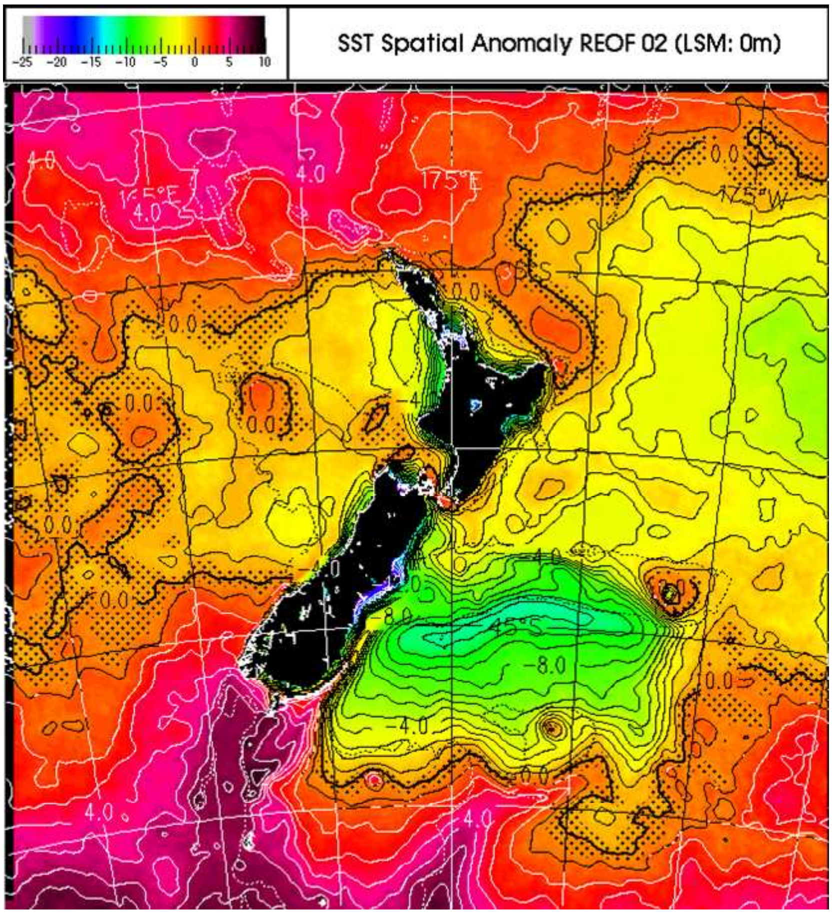


Figure 15a: Rotated Empirical Orthogonal Functions – seasonal anomaly.



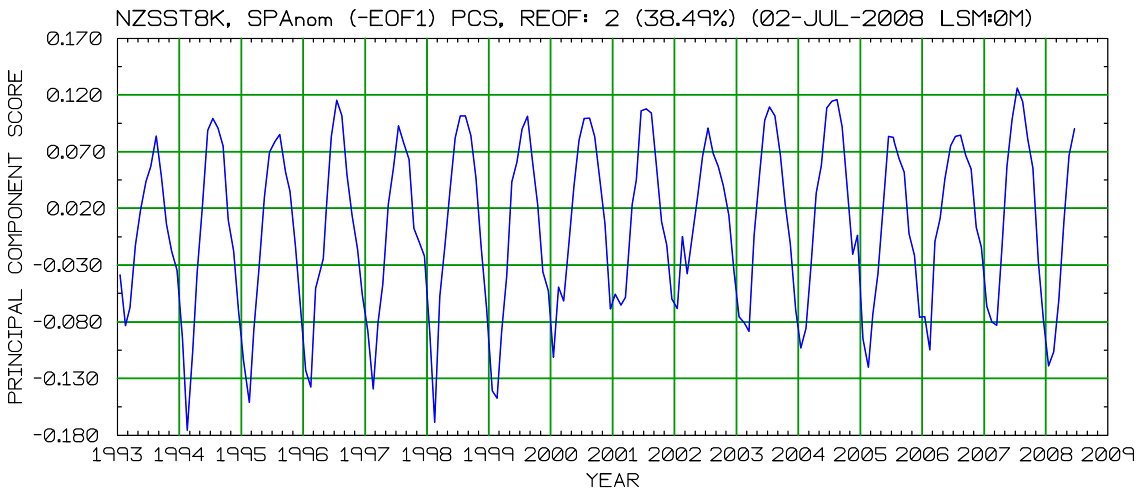


Figure 15b: Rotated Empirical Orthogonal Functions – spatial anomaly.

3.6.4 Monthly mean and anomalies

A complete set of all monthly mean analyses and anomalies (Monthly Mean – Climatology) for all months (January 1993 to June 2008) is given in Appendix 5: Monthly Means and Anomalies: 1993–2008.

Trends/cycles

Regional trends since 1985 (Pathfinder and NSA data combined): For the Tasman Sea area, SST anomalies were most positive (> +0.5) in 1989, 1990, 1998, 1999 and 2001–02 and most negative (< -0.5) in 1987, 1988, and from 1991 to 97, and 2000. Anomalies were less variable than for the other regions. For the STW area, the pattern of highest and lowest anomalies was similar to Tasman but more variable and included more positive years (>+1.0): i.e., also 1986, 1994–96 but not 2002; and fewer negatives (<-1.0): not 1988, 1995, and 1996 but including 2001). Trends in the SAW area do not follow the general pattern of the other two areas. The main positive years were early in the series, 1985–87, with 1991, 1994, and 2002 reaching at least +1.0. There was also more frequent occurrence of negative anomalies from 1988 to 2001, with the main negatives (at least -1.0) being 1988, 1989, 1992, 1993, 1998, and 2001.

New Zealand region since 1993 (NSA data only): From the regional analyses, anomalously high SST years occur in 1998 and 1999 in the three northern-most areas, extending through to late 2001 in subtropical waters. SubAntarctic and Antarctic waters appear less variable but also show high values for the late 1990s (actually from 1999 to 2001). Other highs in these southern areas occurred in 1993–94, and the largest negative anomalies in 1998–99 and 2006–07. From the main seasonal analyses, 1998 stands out as the most anomalous (highest summer and winter SST) across the New Zealand region during the period (EOF1); to the southeast of New Zealand, 1998 and 1999 were years of extreme change (EOF2); and to the west of New Zealand, 1999 was the start of a period with higher mean SSTs (EOF3). From the main spatial analyses, there is more uniformity in SST after 1999 (EOFs 2, 3). All these analyses illustrate the major change in SST that occurred during the late 1990s.

3.7 Upwelling

Upwelling ecosystems provide more than 40% of the world's fisheries catches although they represent less than 3% of the ocean's surface. Upwellings are induced by winds which cause the movement of cold, deep ocean water, rich in mineral salts, to the surface. They are a source of high biological production and subject to significant interannual and interdecadal fluctuations. In upwelling systems, large variations in fish recruitment appear to be due to fluctuations in mortality during the early life-history stages of the fish. Survival through these stages is essentially linked to hydrodynamic structures which favour the retention, enriching, and concentration of plankton and ichthyoplankton. Long term fluctuations in dominant species have been observed in most upwelling systems, such as the alternating sardines and anchovies in the Humbolt, Benguela and Kuroshio currents (source: Fréon, P. http://www.cretaquarium.gr/upload_files/EkpENG/upwelling.pdf).

Upwelling indices presented here are from an exploratory study where it is assumed that an 'upwelling' event has a surface temperature signal, and that this signal is not seriously contaminated by run-off from the land. Accordingly, an upwelling index (UI) has been computed, where

$$UI = SST_{offshore} - SST_{inshore},$$

and 'offshore' and 'inshore' are defined by the bathymetry. A positive UI suggests that the temperature near the coast is cooler than that offshore, and may therefore indicate the presence of upwelling. A negative value is potentially indicative of downwelling. In the results shown here the depth used to define the inshore point is 200 m, and that for offshore is 500 m. Assuming that the calculation is carried out by stepping along either the inshore or offshore bathymetry contour at the resolution of the SST data (i.e., every 1 km) there is no unique method for selecting the location of the terminating point on the other contour. A number of methods were tried, including

1. an east – west search;
2. a radial search to find the nearest point on the second contour (up to some maximum distance, 500 km in the case of the method used here); or
3. a combination of these two methods, where an east-west search is applied first, and if that fails, then a radial search is used.

In the results reported here (Figures 16a–g), method 3 has been used. The values of this index are expected to be sensitive to the depths chosen for the computation. The Upwelling Index (500 m – 200 m) was estimated for all 1 km sections along the 200 m isobath, and for all monthly mean SST data between January 1993 and June 2008. From these data, indicative time series were calculated for seven locations indicated in Table 6

Table 6: Locations at which Upwelling Index time series were computed.

Location	Latitude (°S)	Longitude (°E)
Hokitika Canyon	42.66	170.70
Fiordland	44.89	167.22
Foveaux Strait (West)	46.58	167.10
Kaikoura Canyon	42.44	173.66
Ngawi	41.65	175.23
East Cape	37.57	178.61
North East Shelf	35.00	174.20

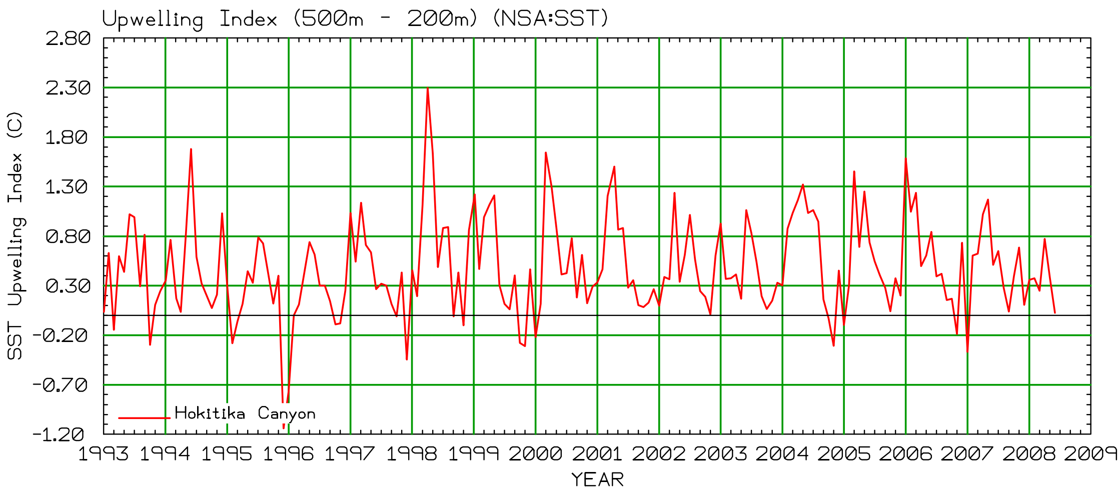


Figure 16a: Upwelling Index for the Hokitika Canyon.

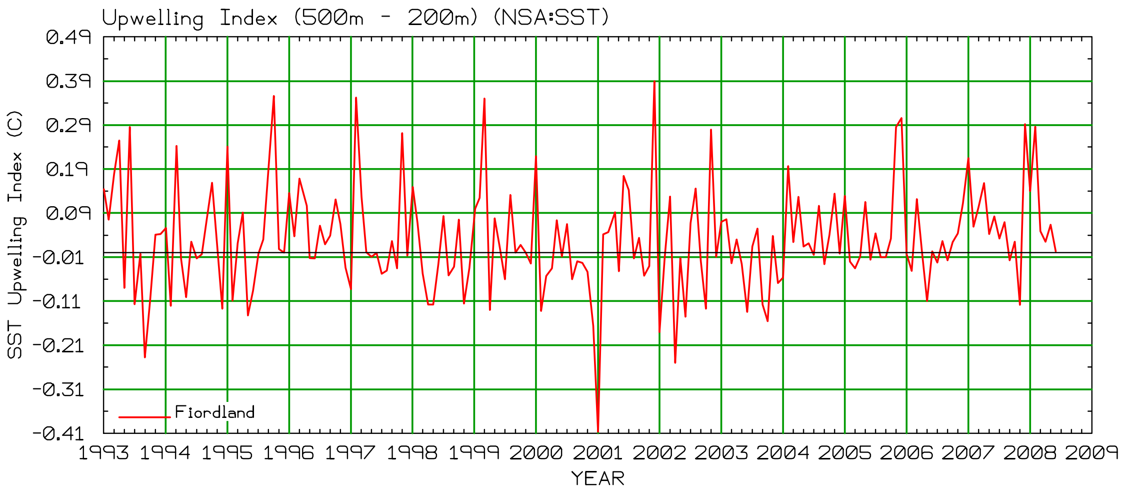


Figure 16b: Upwelling Index for Fiordland.

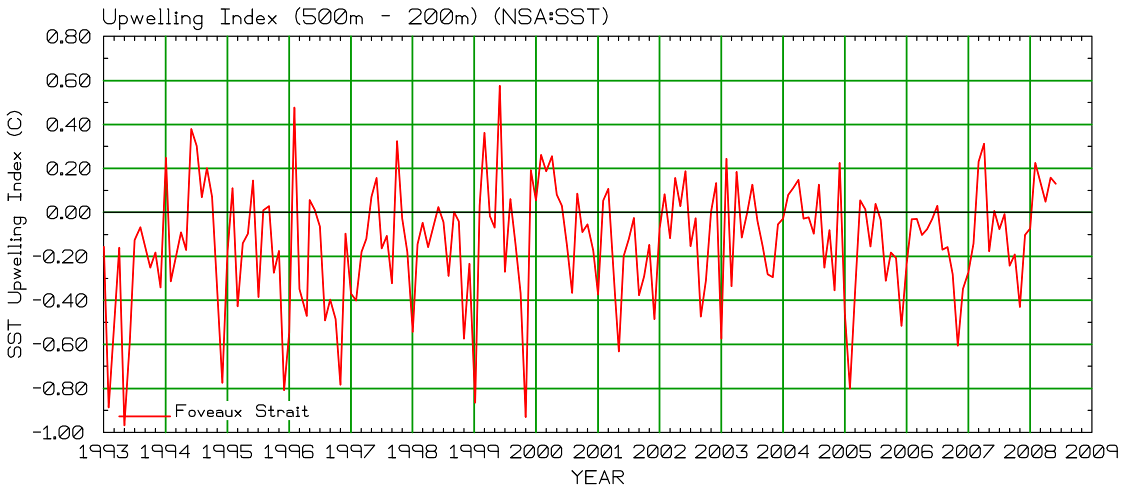


Figure 16c: Upwelling Index for Foveaux Strait (West).

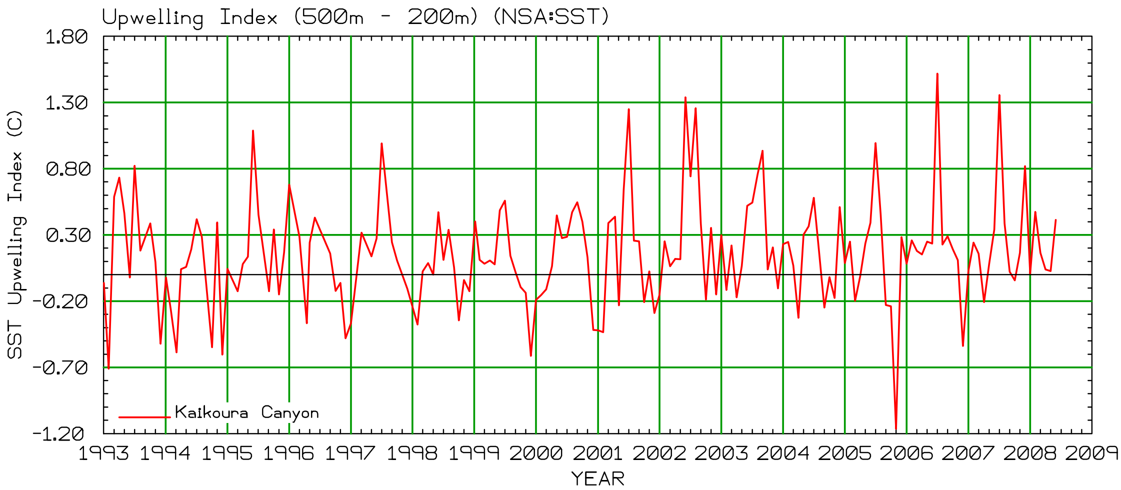


Figure 16d: Upwelling Index for the Kaikoura Canyon.

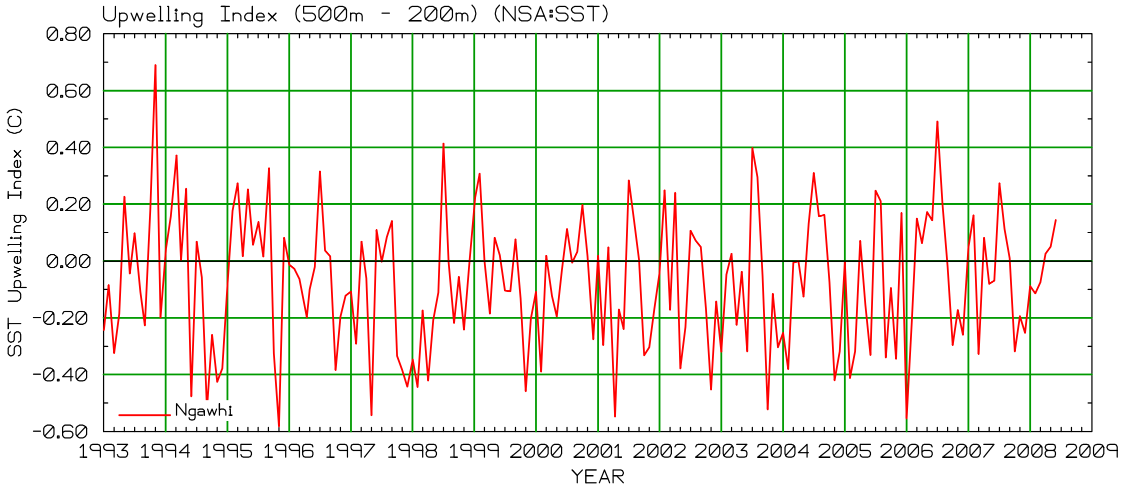


Figure 16e: Upwelling Index for the Ngawi site (Cook Strait).

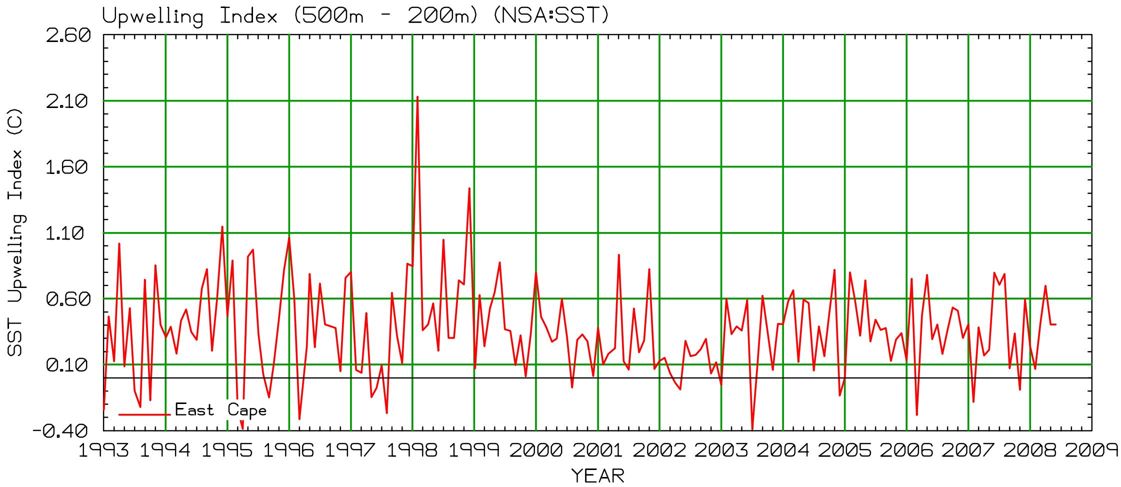


Figure 16f: Upwelling Index for East Cape (north).

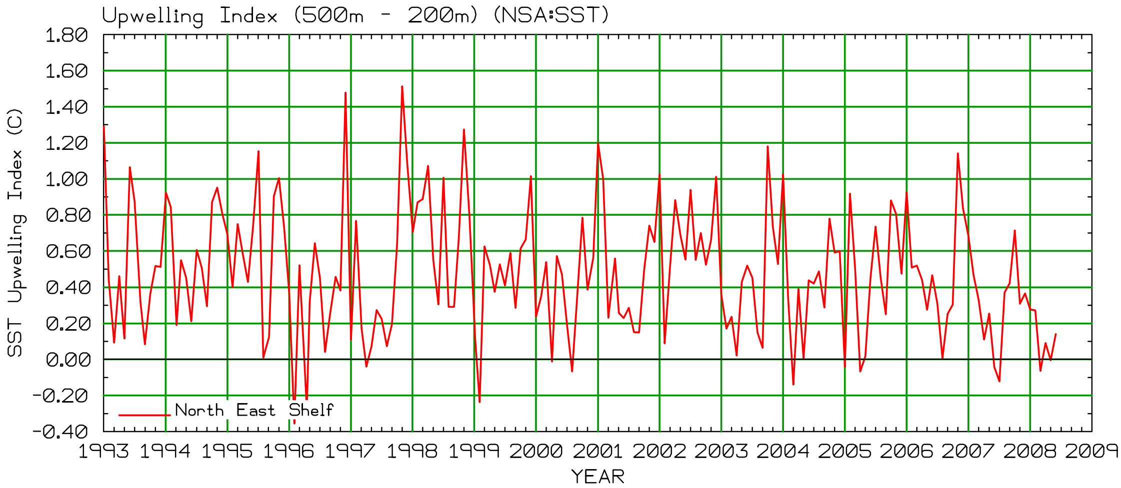


Figure 16g: Upwelling Index for a representative location on the north east shelf.

Trends/cycles
Upwelling indices presented here are preliminary and need verification. Detailed analysis of the type of trends presented here in relation to other climate and ocean variables, such as along-shore wind stress and currents, could help establish the validity of these indices.

There are some cycles in the series presented from 1993, but trends are difficult to determine because the time series is still relatively short with respect to major climatic changes (e.g., regime shifts). Hokitika has a high frequency of positive values that exhibit seasonal cycles (usually peaking in summer and autumn). The maximum peak occurred in 1998 and maximum values pre-1998 appear less than those post-1998. Values for the winter period (June–August), when many fish species (e.g., hoki, hake, and silver and common warehou) spawn in the area, are lowest in the late 1990s.Values for East Cape and the northeast shelf are also strongly positive, with some high peaks in 1998, and some suggestion (mainly for the northeast shelf) of more positive values in late spring/early summer. In contrast, indices values for Foveaux Strait and Ngawi are mostly negative and, along with Kaikoura, have more negative values in late spring/early summer. There are no clear patterns in the indices for Fiordland.

Changes in the timing and extent of upwelling systems in New Zealand waters have been linked mainly to primary productivity and harmful toxic algal blooms (e.g., Chang et al. 2003, Zeldis 2004, Zeldis et al. 2004, 2008, Longdill et al. 2008). For example, Zeldis et al. (2008) found that negative SOI, strengthened NNW along shelf wind stress, and cooler SST were associated with upwelling that triggered increased phytoplankton production and resulted in higher farmed mussel yields in Pelorus Sound. Attempts have also been made to link factors associated with upwelling (winds, vertical mixing, nutrients) with fluctuations in hoki year class strength off the west coast of the South Island (Bull & Livingston 2001, Francis et al. 2006) but the most significant correlation (with nitrate concentrations) reversed during the time series and this has not yet been explained.

3.8 Ocean temperature (0–800 m depth)

New Zealand's longest time series of subsurface temperature come from repeat expendable bathythermograph measurements made from container ships on two transects in the New Zealand region: between Auckland and either Suva or Honolulu and between Sydney and Wellington. They were instigated by Dean Roemmich and Bruce Cornuelle of Scripps Institution of Oceanography (Roemmich & Cornuelle 1990) and are now collected as part of collaboration between Scripps Institution of Oceanography, CSIRO, and NIWA. Analyses of the subsurface temperature field using these data include Sutton & Roemmich (2001) and Sutton et al. (2005). There are three outputs for each series: the 'raw' data (i.e., colour contour figure of temperature/depth/time); an index of the upper ocean temperature (0–100 m) deseasoned (i.e., seasonal trend removed); and an index of deep temperatures (100–500 m) deseasoned.

3.8.1 Eastern Tasman ocean temperature: Wellington to Sydney (1991–2007)

The ocean between Wellington and Sydney has been sampled roughly four times per year since 1991. The index presented for this transect (Figure 17) is for the most eastern section closest to New Zealand (161.5° E and 172° E). The eastern Tasman is chosen because, firstly, it is closer to New Zealand, and, secondly, it has less oceanographic variability which serves to mask subtle interannual changes. The western Tasman is completely dominated by the highly variable East Australian Current. The section of the transect shown is along fairly constant latitude, and so is unaffected by latitudinal temperature and seasonal cycle variation. The upper panel shows the temperature averaged along the transect between the surface and 800 m and from 1991 to the most recent sampling.

3.8.2 Northern ocean temperature: Auckland to Suva (1987–2007)

The ocean between has been sampled roughly four times per year since 1987. There are three sets of indices presented for this transect: southern, central and northern (Figures. 18a–c) as the transect crosses a range of ocean conditions and there is much higher variability in mean and annual cycles than for the eastern Tasman transect. However, some areal averaging is useful because it lessens the noise caused by mesoscale (order of 100 km) and smaller ocean variability to allow interannual signals to be resolved.

The indices for the nearest to New Zealand sections of both time series are compared in Figure 19, i.e., the western section of the Eastern Tasman transect in and the southern section of the Auckland to Suva transect (34.45° S to 30° S). Note that the southern end of the Auckland to Suva line is much more variable than the eastern Tasman − this is because the dynamically active East Auckland Current is sampled by the northern section. The low variability and dynamism of the eastern Tasman makes it an ideal place to measure subtle interannual changes.

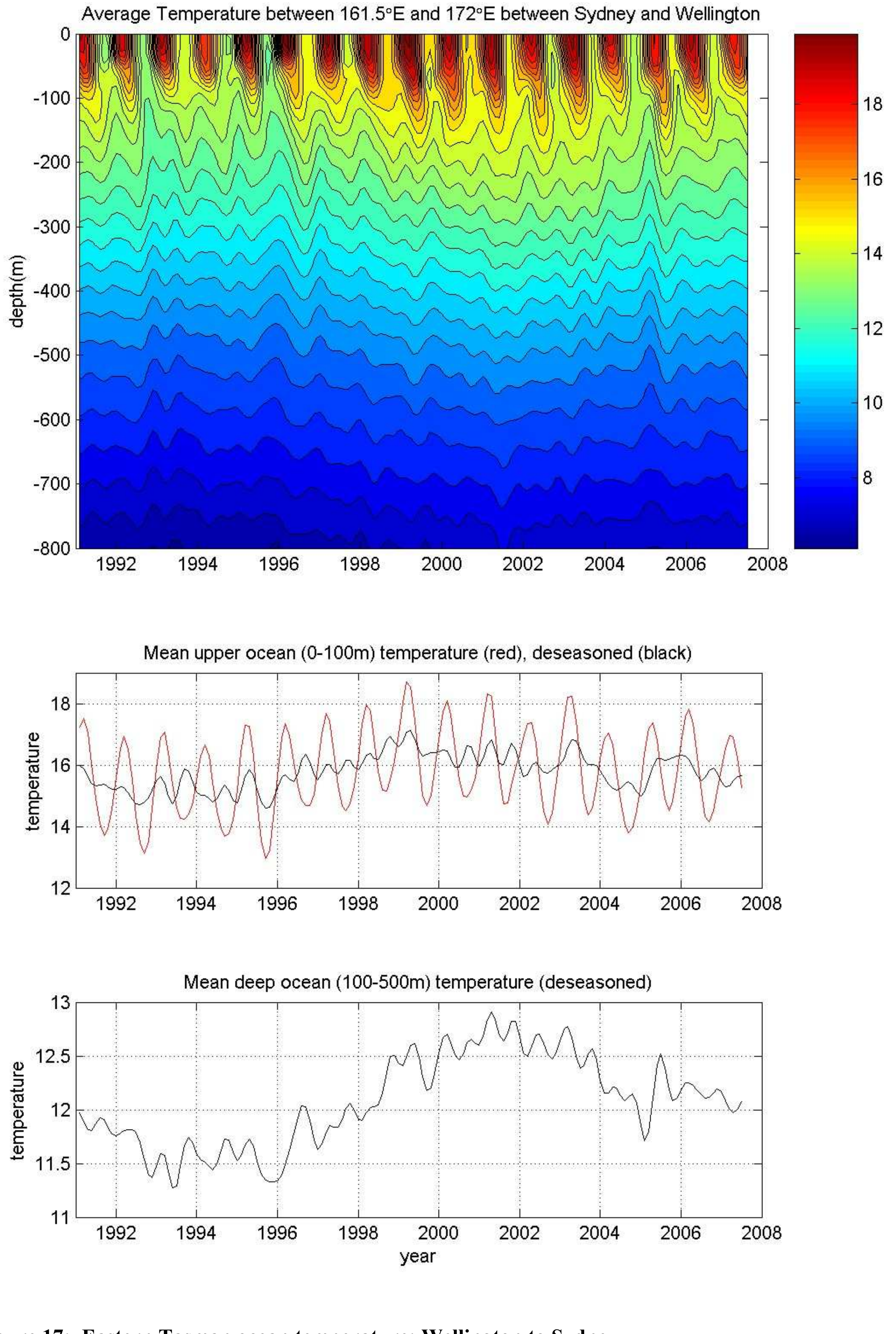


Figure 17: Eastern Tasman ocean temperature: Wellington to Sydney.

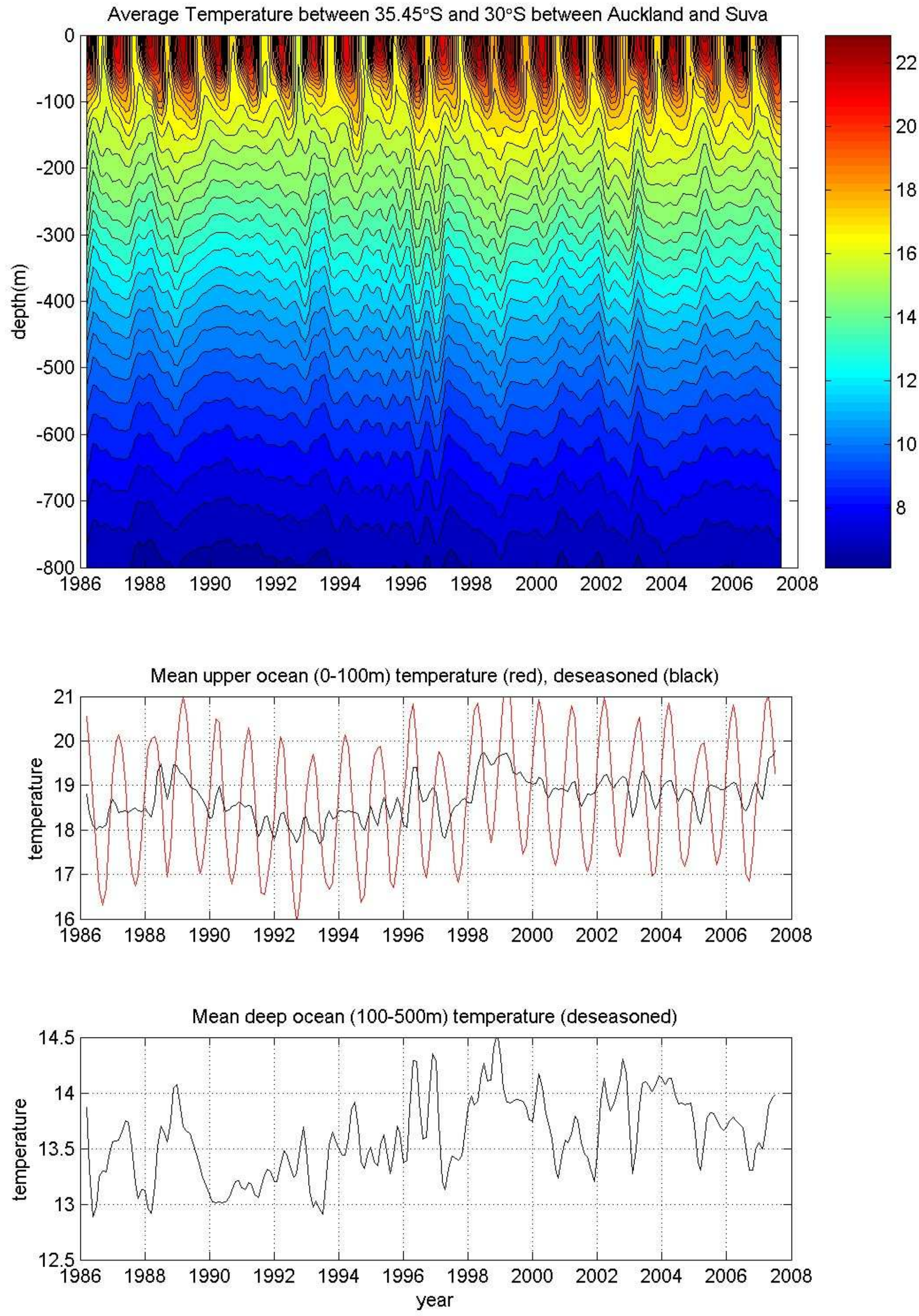


Figure 18a: Northern ocean temperature: southern section, Auckland to Suva.

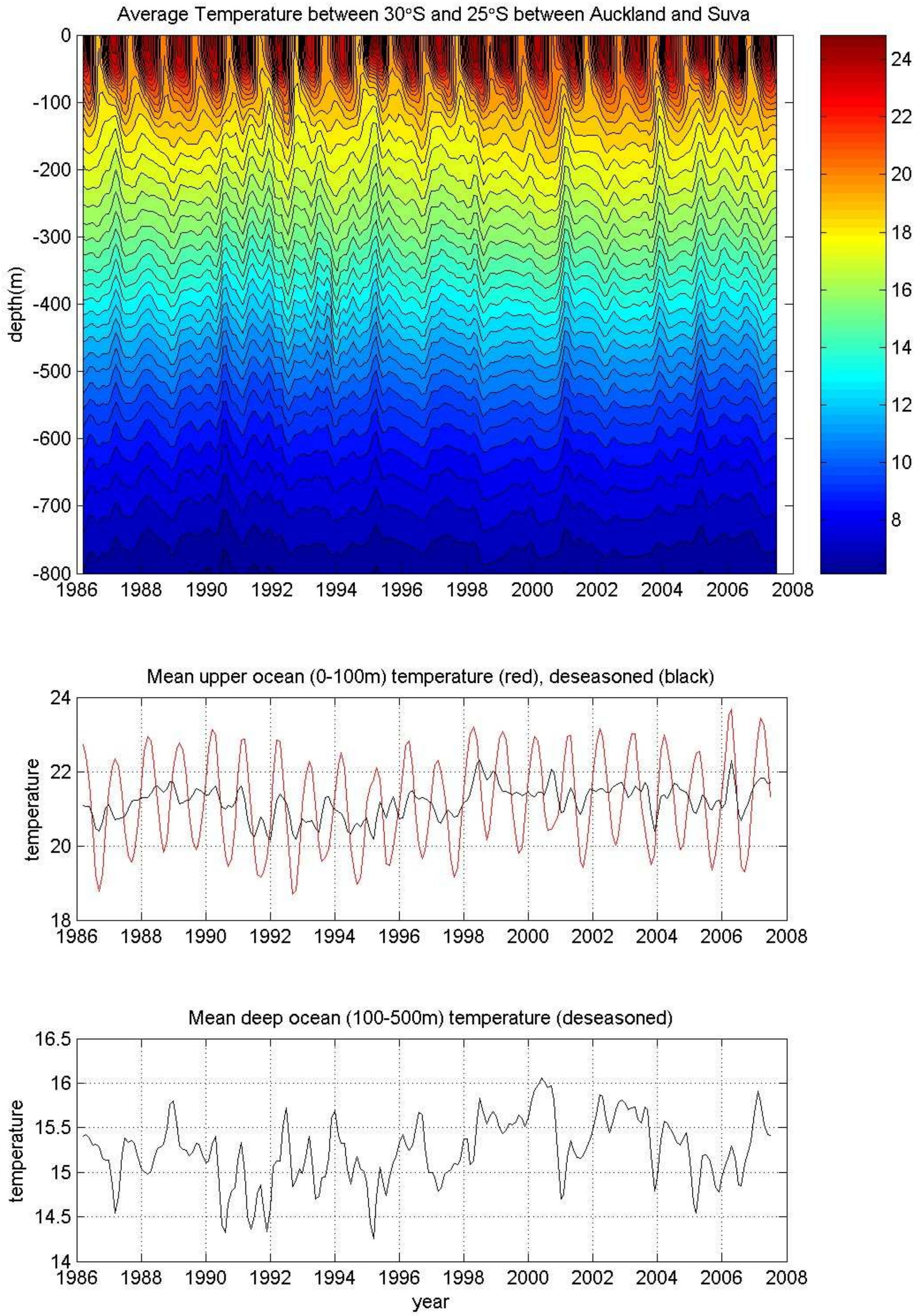


Figure 18b: Northern ocean temperature: central section, Auckland to Suva.

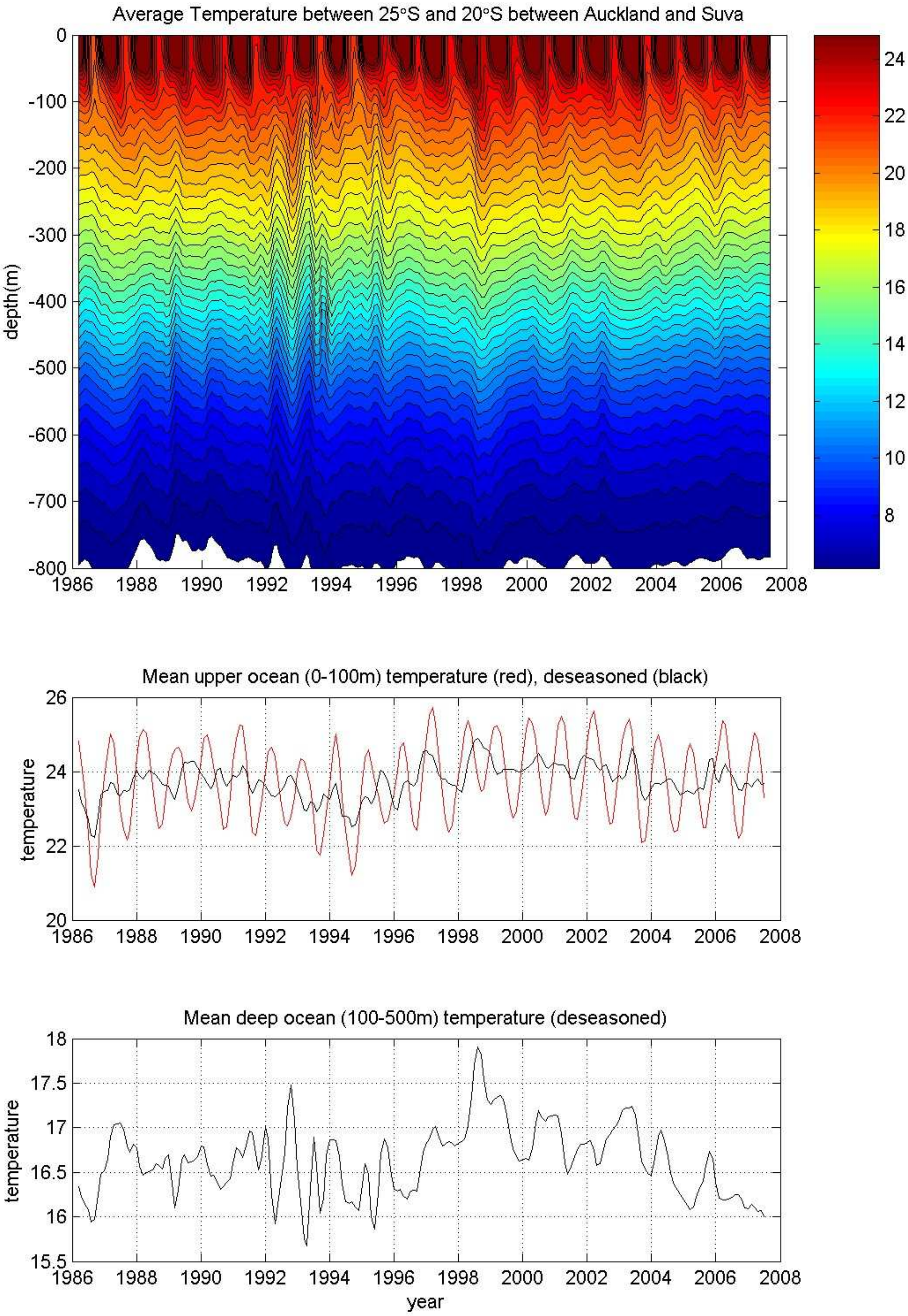


Figure 18c: Northern ocean temperature: northern section, Auckland to Suva.

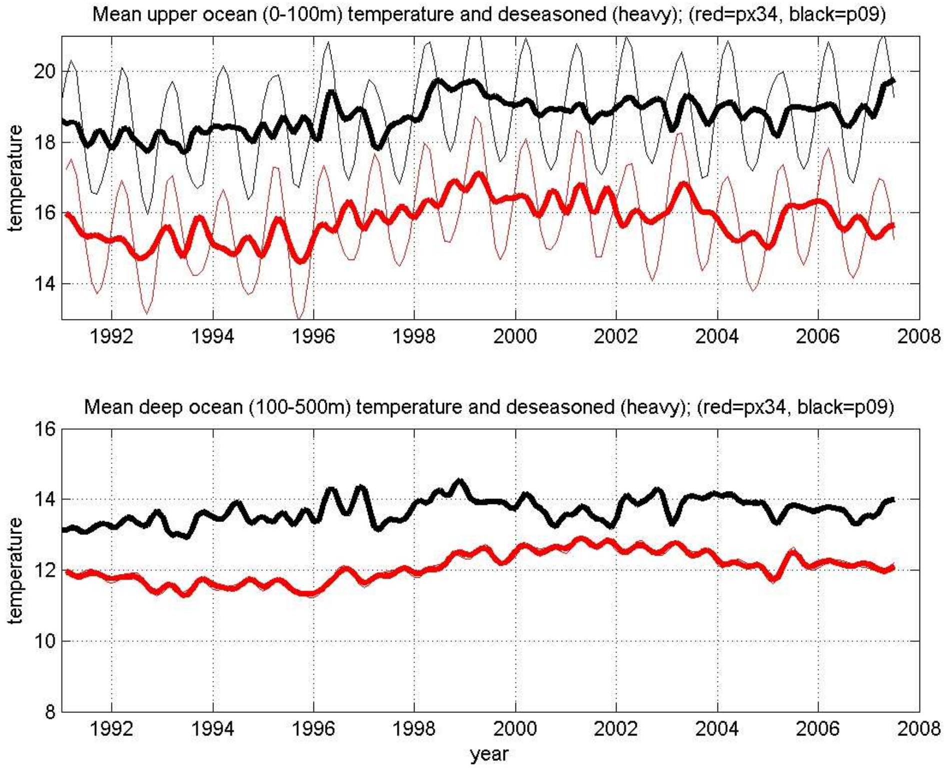


Figure 19: Comparison of the nearest New Zealand shore transects; eastern section of the eastern Tasman transect (red) and southern section of the northern transect (black).

Trends/cycles

The seasonal cycle is clearly visible in the upper 100–150 m. There is a more subtle warming signal that occurred through the late 1990s, which is apparent by the isotherms increasing in depth through that time period. This warming was significant in that it extended to the full 800 m of the measurements (effectively the full depth of the eastern Tasman Sea). It also began during an El Niño, when conditions would be expected to be cool. Finally, it was indicative of a large-scale warming centred on 40° S that had hemispheric and perhaps global implications. This warming was discussed by Sutton et al. (2005) who examined the local signals, Bowen et al. (2006) who studied the propagation of the signal into the New Zealand area, and Roemmich et al. (2007), who examined the broad-scale signal over the entire South Pacific and hypothesised that the ultimate forcing was due to an increase in high latitude westerly winds effectively speeding up the entire South Pacific gyre.

The panels in Figure 19 show average temperatures for the depth ranges 0–100 m and 100–500 m with seasons both included and removed for this eastern end of the transect. These clearly show the warming through the 1990s, but also show that there has been some cooling since 2001, although to nothing like the levels of the early 1990s.

It is difficult to judge whether this variability was part of a cycle, as the time series is not long enough to have studied more than one of these events. We are now monitoring these data and updating this analysis regularly to watch for any new changes.

Comparison of ocean temperature and SST observations

SST products give high-resolution coverage of the New Zealand area, but are somewhat limited as only the very surface of the ocean is measured. This surface temperature can be expected to be representative of the upper mixed layer of the ocean in wintertime windy conditions, but may be significantly different in calm summertime conditions when a shallow thermocline forms. This kind of effect was described by Sutton et al. (2005) who showed that the trend SST is significantly noisier that the upper ocean mean temperature (0–100 m), even on interannual time scales.

Comparison of ocean temperature and SSH observations

Changes in the relative height of the sea surface are measured to within a few centimetres every 10 days by satellite altimeters (e.g., http://www.aviso.oceanobs.com/). The changing height of the sea surface provides information about the changing surface currents because the surface currents are associated with slopes in the sea surface. It does not provide information about the mean currents, because the altimeter measures only changes from the mean condition. The sea surface height (SSH) also provides information about the heat content of the water. This is because warm water is less dense and so stands taller. A clear example of this was seen during the late 1990s Tasman warming when satellite SSH increased consistent with the change expected by the measured temperature (Sutton et al. 2005). This sea level change of about 10 cm was also measured by coastal sea level gauges.

Where SSH is slightly limited as a tool is that it provides information about the integrated or averaged temperature changes but does not define where in the water column those changes occurred. This is why combining it with direct measurements such as the XBT datasets (above) or Argo data (below) is preferable.

Argo- emerging technology

Argo is an international programme committed to deploying an array of 3000 freely drifting profiling floats in all of the world's oceans. These floats typically 'park' at a depth of about 1000 m, before sinking down to around 2000 m and then profiling to the surface every 10 days (see e.g., http://www.argo.ucsd.edu/). The resulting information available includes temperature and salinity profiles between the surface and 2000 m and estimates of the currents at the parking depth from the changing positions of each profile.

As a result of Argo, new measurements of the mid-depth ocean have become available in the New Zealand region since around 2000, and since the 3000 float design goal was reached in 2007, there is now adequate coverage to study future interannual variability.

Examples of possible analyses are shown in Figure 20 which shows the temperatures measured at 900 m from all of the Argo profiles collected in the New Zealand region. A further example, of velocity at 900 m, is shown in Section 3.11 on currents.

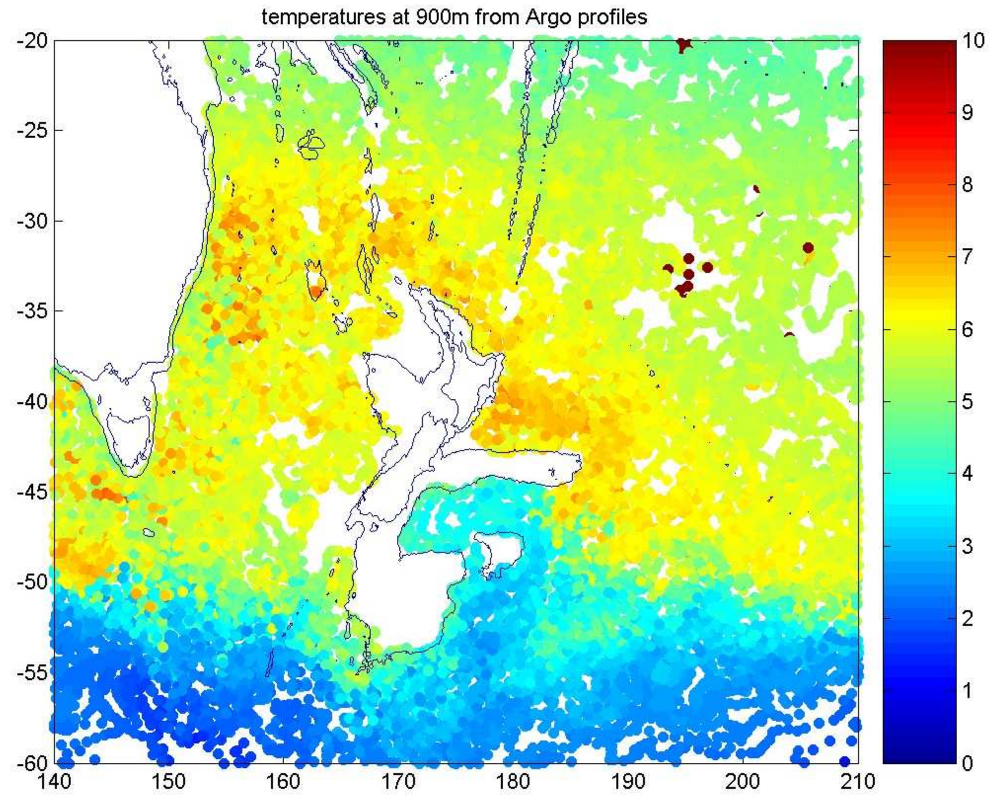


Figure 20: The temperature as measured at 900 m from all available Argo floats in the New Zealand region.

3.9. Sea surface height (SSH) (1993 – present)

On a broader scale than subsurface SST, sea surface height (SSH) data provide estimates of changes in the upper ocean heat content and are available from satellites since 1993. Sea surface height provides a measure of ocean heat content, because warmer water is less dense and therefore stands taller. It does not resolve where the temperature changes occur through the water column, but most of the changes occur in the upper ocean.

Sea surface height data are indicative of the heat content of the ocean (as opposed to localised warming at the surface as measured by SST) and enable surface currents to be inferred. These data would be useful to include in a report of this type but cannot be provided in the timeframe required. Work is now underway to continue analysis of SSH from 2008−09 and indices could be developed for any future editions of this report.

An example of the outputs from satellite altimetry on a global scale is shown in (Figure 21, from http://bulletin.aviso.oceanobs.com/html/produits/aviso/welcome_uk.php3).

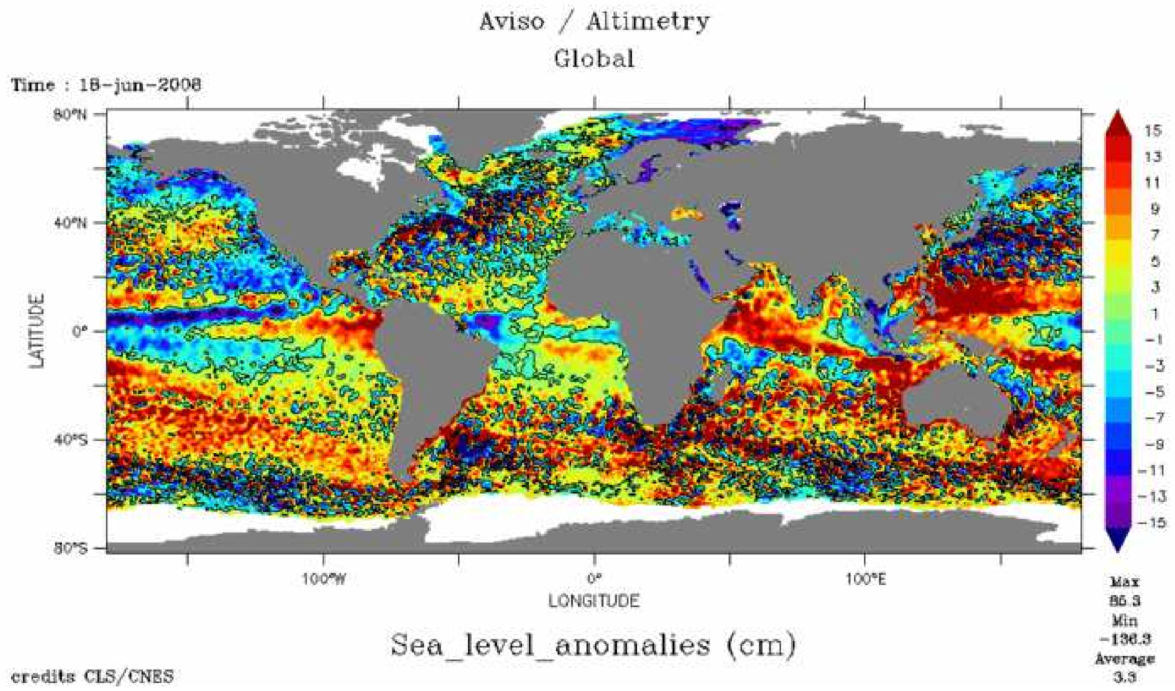


Figure 21: Global satellite altimetry, 18 June 2008.

Indices that have been used in previous fisheries related analyses (Dunn et al. 2009a), from 1992 to 2006 are presented, but have not been updated. These were derived for the Fishery Management Areas (FMAs, see Figure 22) 1–9 (Figure 23).

Trends/cycles

The time series from 1992 suggests that there has been a trend of increasing SSH from the early 1990s to 1999, followed by a flattening off or slight decline through to 2006. For FMA 7 (west coast South Island), this is consistent with the general pattern of increasing SST during this period, described earlier (see Section 3.5, Figure 9 Jackson Bay, Section 3.6, Figures 12 (Tasman Sea) and 14b, Section 3.8 Figure 17). Similarity can also be seen between the SSH for FMA 1 (northern NZ) and the southern Auckland to Suva transect in Section 3.8, Figure 18a.

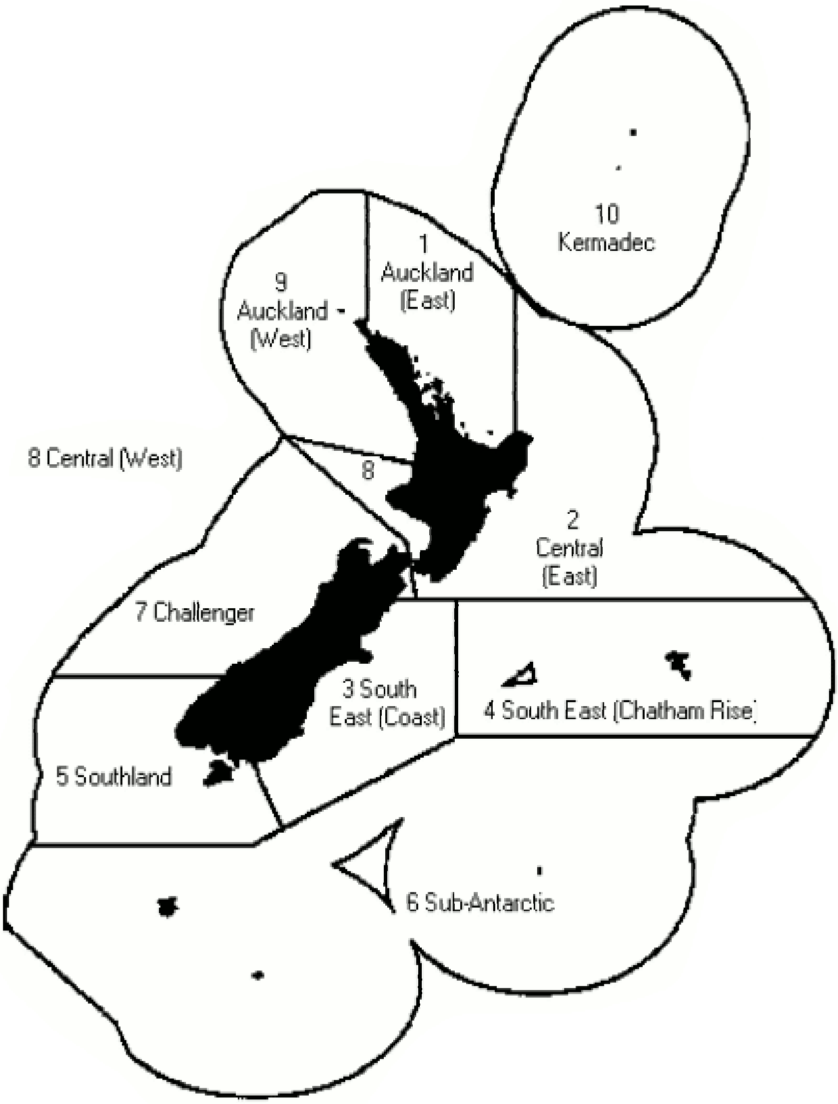


Figure 22: New Zealand Fisheries Management Areas (FMA) boundaries and labels. Reproduced from the MFish website (www.fish.govt.nz).

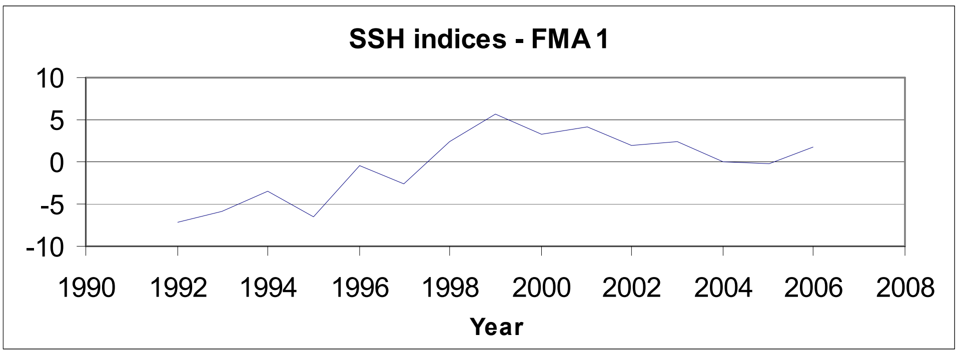
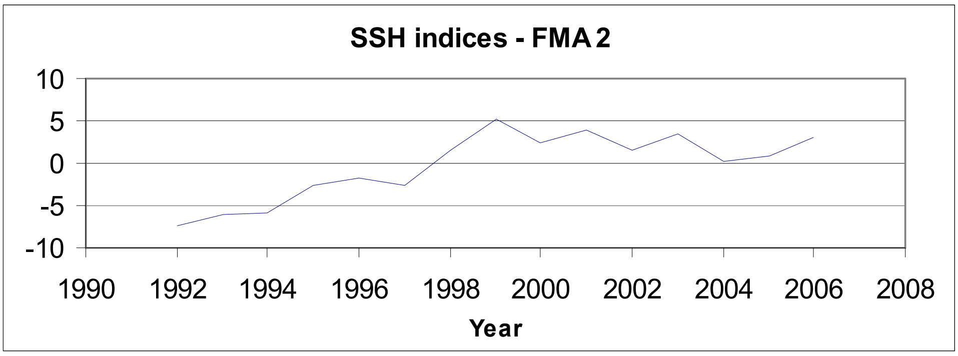
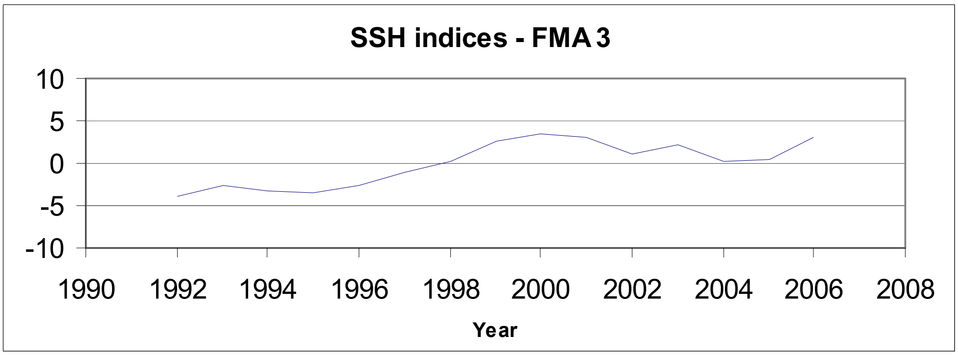
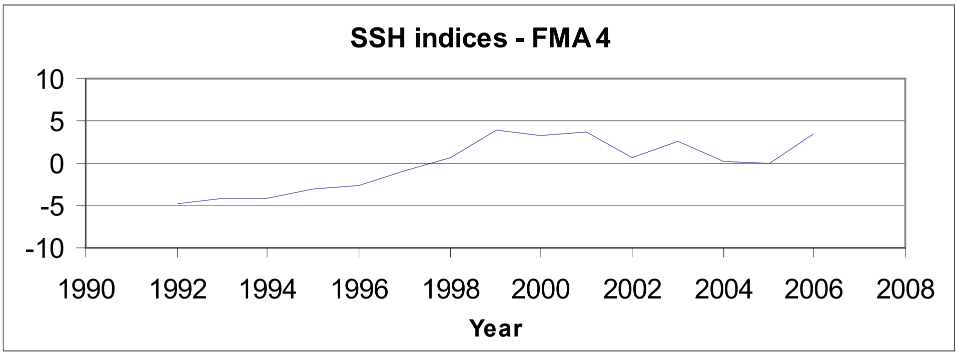


Figure 23: SSH indices for Fishery Management Areas (FMAs) 1–9, 1992–2006 (from Dunn et al. 2009a).







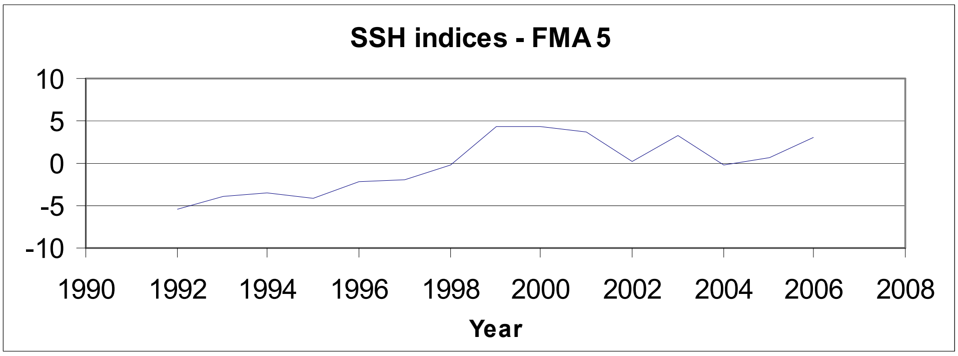
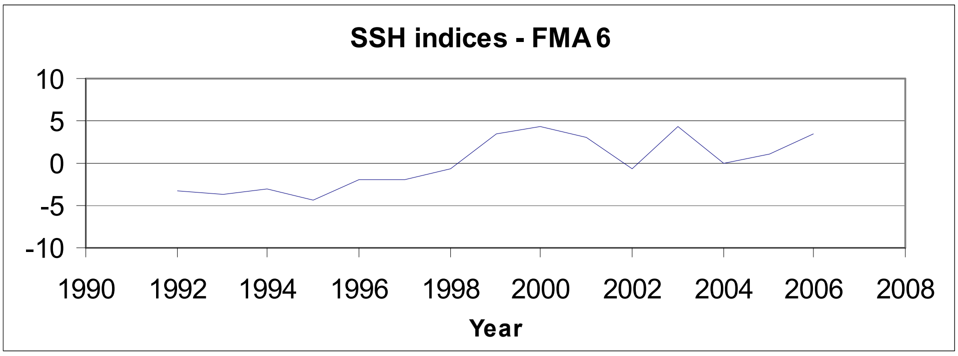
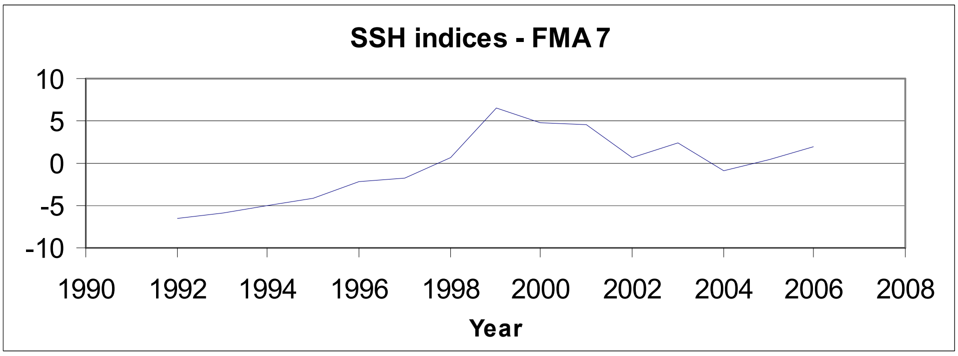
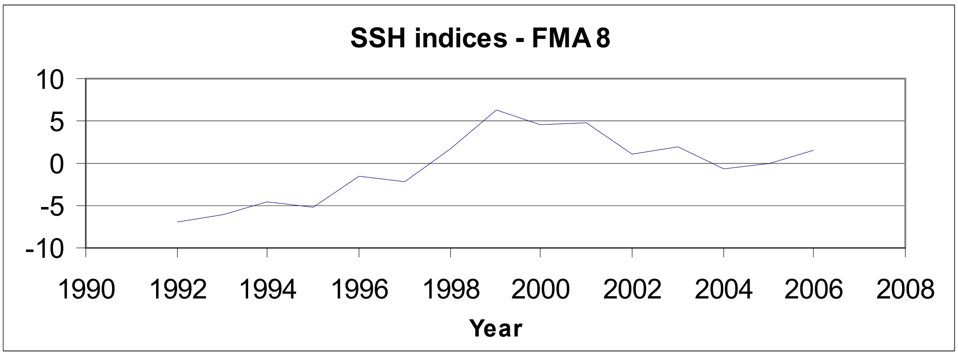


Figure 23 *continued*: SSH indices for Fishery Management Areas (FMAs) 1–9 (from Dunn et al. 2009a).







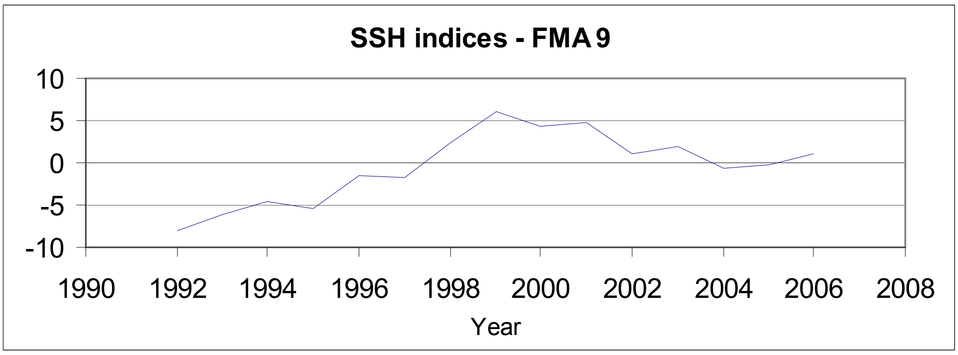


Figure 23 *continued*: SSH indices for Fishery Management Areas (FMAs) 1–9 (from Dunn et al. 2009a).

3.10 Ocean colour regional analyses

3.10.1 Introduction

Primary production (PP) by marine phytoplankton is fundamental to the functioning of marine ecosystems as the process determines the energy entering the base of marine food webs which influences the carrying capacity of marine ecosystems (e.g. Ware & Thomson, 2005). Before 1997, studies on the spatial and temporal variability of marine primary production and phytoplankton biomass required extensive ship-based sampling. Since 1997, synoptic estimates of surface chlorophyll-a concentration (Chl), a proxy for phytoplankton standing stock, have been available from Earth observing satellite sensors. On a global scale, high PP (which is estimated using an algorithm that incorporates Chl, light, depth distribution, nutrients, and the amount of carbon produced per unit of Chl) and Chl, correlates well with high fisheries yields (e.g., Sherman et al. 2005). On a local scale, there is significant and poorly understood subtlety in the linkage between PP, phytoplankton biomass, and fish abundance and distribution (e.g., McClatchie et al. 2005).

Ocean colour data are used in fisheries management around the world to characterise and monitor the environment of living marine resources, for example by observing changes in the spatial and temporal distribution of production which may affect recruitment (Platt et al. 2003), to detect interannual differences in the frontal structures that may be important to fisheries (Polovina et al. 2001, Bograd et al. 2004) and to map the spatial and temporal extent of the effect of climate (e.g., El Nino) on primary productivity (Wilson & Adamec 2001).

Satellite-based estimates of PP in New Zealand waters are available (e.g., Willis et al. 2007b), but validation of these estimates is at an early stage. Until this validation work is further advanced (through work in New Zealand waters by the FRST-funded Coasts and Oceans OBI at NIWA), this report has used satellite observations of Chl rather than PP. Ocean colour is a proxy for the Chl concentration (and therefore active PP) at the ocean surface and methods of estimating Chl have had preliminary validation in New Zealand waters (Pinkerton et al. 2005). At the coast, the relationship between colour and Chl can be complicated by particulates from river and land run-off. In the open ocean, ocean colour is a fairly reliable measure of Chl concentration and we have focused on this area in this report.

Ocean colour is used here to describe the seasonal patterns of chlorophyll-a blooms in the New Zealand EEZ. The data used are the monthly composited 9 km data regridded to ¼ degree, from the SeaWifs series (October 1997–December 2007) .

3.10.2 New Zealand Chl analyses

The overall mean of these data clearly shows enhanced Chl east of New Zealand along the Chatham Rise, and in general along a band in the Tasman Sea (Figure 24a). This band appears to correspond with the Subtropical Front, where macronutrient-rich, micronutrient-poor Subtropical Water (STW) converges with micronutrient-rich, macronutrient-poor SubAntarctic Water (SAW). It is generally accepted that the merging of these waters provides the conditions necessary for enhanced phytoplankton growth, and that under the right conditions – increased light availability during spring, or increased wind mixing during spring and autumn – a bloom results.

The region east of New Zealand, and especially along the Chatham Rise also exhibits the highest variability, no doubt a consequence of the large blooms that occur here (Figure 24b).

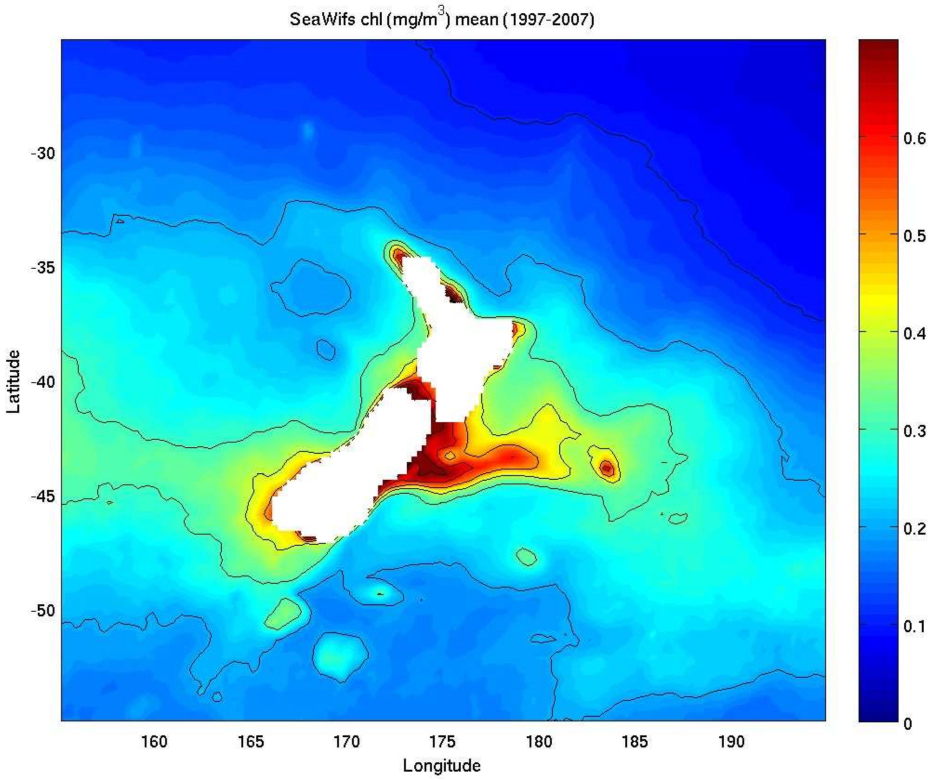


Figure 24a: Average of Chl (mg/m^3), 1997–2007.

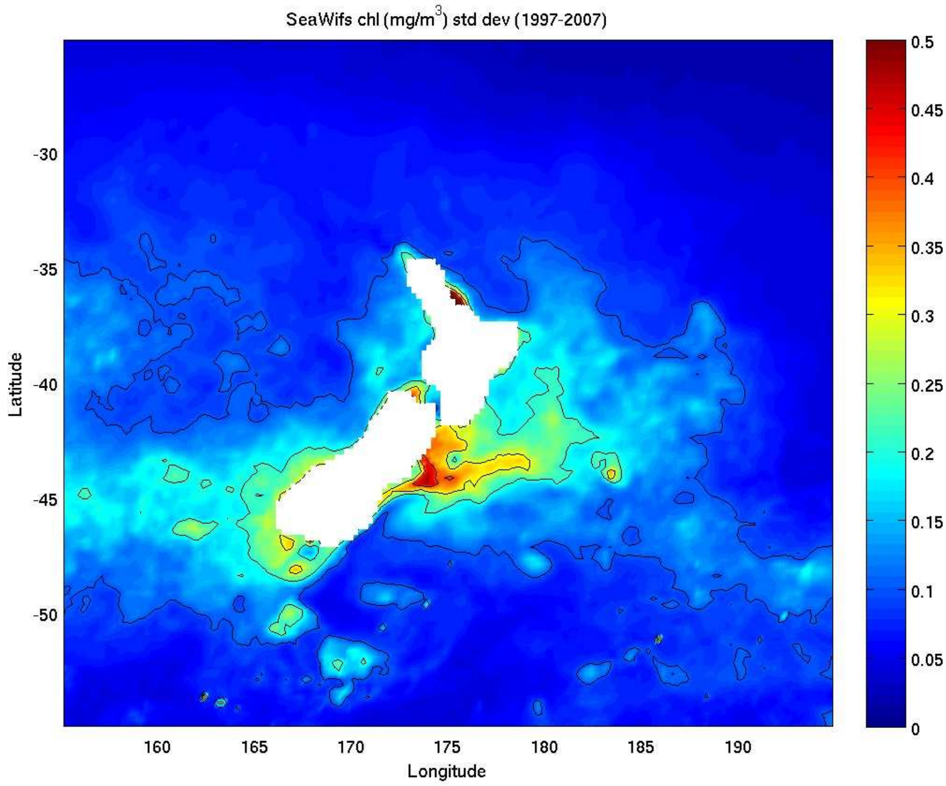


Figure 24b: Standard deviation of Chl (mg/m^3), 1997–2007.

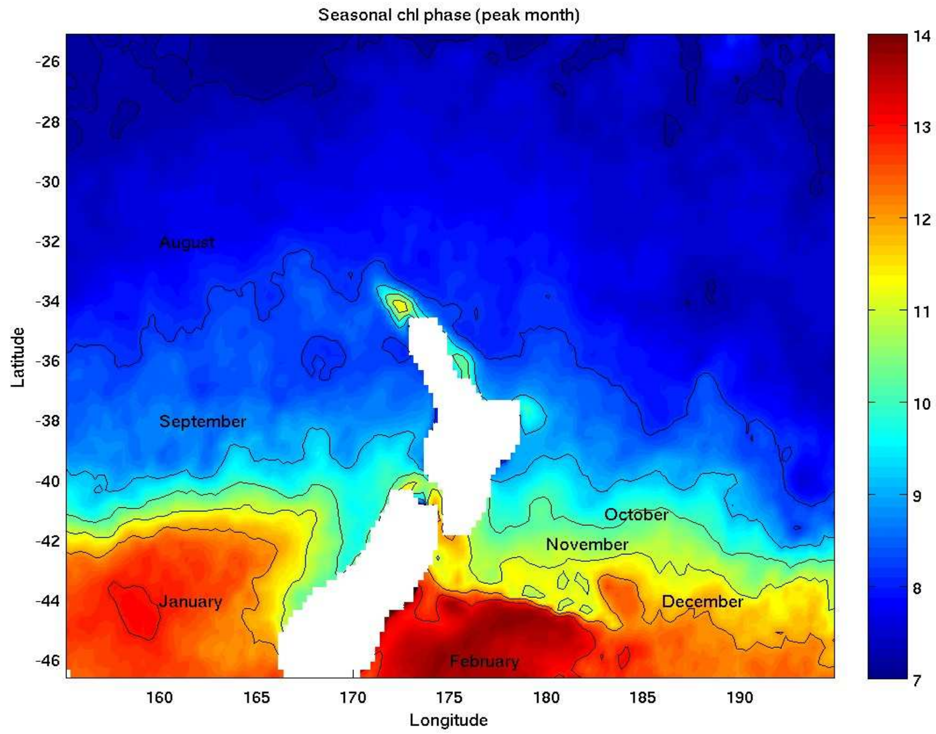


Figure 25a: Seasonal phase of the spring and autumn blooms.

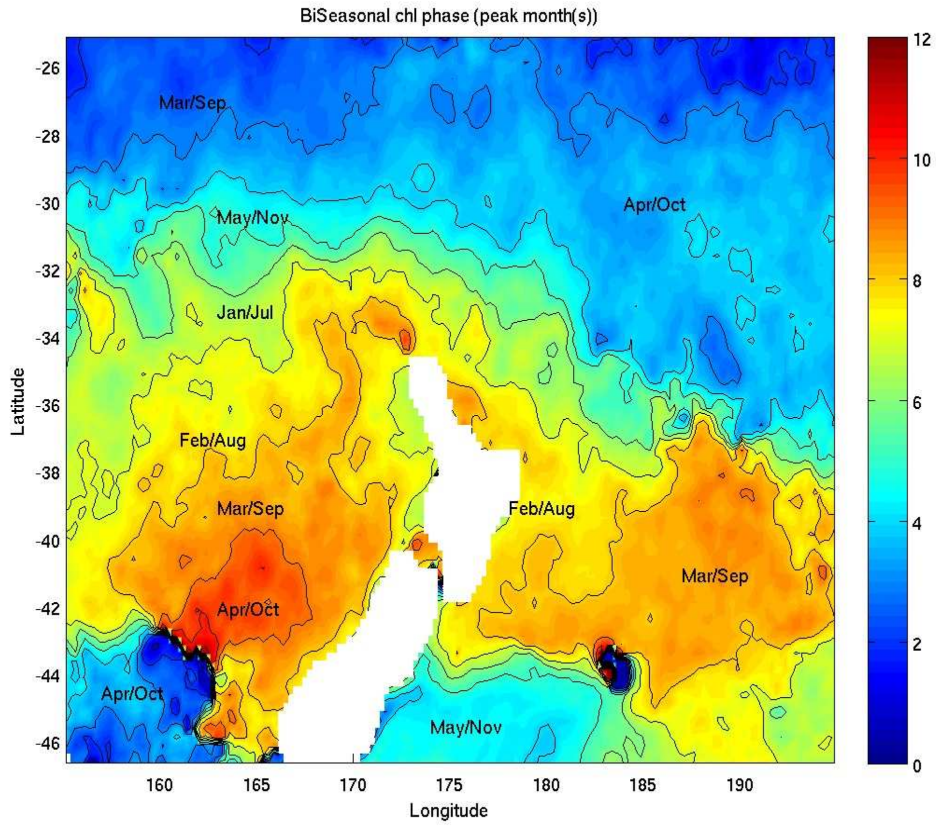


Figure 25b: Bi-seasonal phase of the spring and autumn blooms.

To study the timing of the blooms, seasonal and biseasonal cycle harmonics were fitted to the data. The results show a clear peak in spring, which explains most of the variability north of the North Island. Interestingly, the peak bloom varies in its timing across the region (Figure 25), appearing to propagate from north to south as the light availability increases with latitude later in the year. However, it is important to note that this regular harmonic fit does not explain much of the variability in the regions where the Chl variability is strongest.

The spring bloom peaks in August to the north of New Zealand and September–October around the North Island. Around the South Island, the peak bloom is not until summer (January–February, Figure 25a). The twice yearly cycle partly accounts for the fact that the autumn is not always a true minimum and for the various timings between spring, summer, and autumn (Figure 25b).

The goodness of the fit of these harmonics is not very good, except in the north region. Thus, while we gain some insight into the timing and propagation of the blooms, we find that most of the variability remains unexplained. To overcome this, principal components were calculated for the data. These offer the advantage of allowing for irregular timings for overall spatial patterns. In order to carry out this analysis, the area from south of 46º S has been omitted because there are many gaps in the data, particularly from winter months.

Each principal component consists of a spatial pattern (EOF) and its associated amplitude time-series. The EOF is a map of Chl concentration which must be multiplied by the appropriate amplitude from the time-series. The first EOF (spatial pattern) with its time series shows a strong seasonal cycle in agreement with the harmonic analysis (Figure 26). The blue region east of the North Island indicates the peak in the spring bloom; this is because the negative spatial pattern is multiplied by the negative amplitude for spring. Likewise, the red region along the Chatham Rise indicates the summer bloom when the time series amplitudes are positive. The main point is that the annual phytoplankton bloom explains a large part of the annual variability, but occurs at different times around New Zealand.

The second EOF shows a peak in Chl east of New Zealand and along the Chatham Rise beginning each spring and through the summer (Figure 26). The time series is somewhat seasonal, with a secondary peak during the summer or autumn, but is clearly not regular from year to year. Together these first two principal components explain over half the variance for the entire region, whereas the harmonic analysis did not explain much overall variance. This is because the timing and duration of the blooms varies from year to year.

A correlation analysis between the EOFs and the original data shows that the first pattern explains mostly variations around the northern portion of the North Island and to its north (50–90%), while the second EOF explains about 50% of the variations on the Chatham Rise. The third pattern (not shown) explains little overall variance (6%), but represents a strong pattern along the south of the Chatham Rise. This pattern is probably associated with the Subtropical Front, and its time series is entirely episodic.

Overall, we can conclude that the New Zealand EEZ region exhibits a spring bloom that migrates southward with the sun each year. However, the timing of this bloom differs from year to year, and is complicated by secondary blooms throughout the summer and into autumn. The region that exhibits the highest levels of Chl (on and south of the Chatham Rise) appears to be largely episodic in nature. That is, the seasonal and biseasonal patterns leave most of the variance for this region unexplained. These events may be related to either atmospheric wind or oceanographic current events, or both. To investigate this it will be necessary to perform statistical comparisons between the ocean colour data and other indicator data sets, such as sea surface height, winds, and SST.

Chlorophyll values at specific sites are given in Figures 27–29. Two of these are positions are along lines of longitude to the west and east of New Zealand. Note that the southernmost location on the western transect appears to have higher Chl values, similar to the Chatham Rise, but this location is relatively close to shore and more likely to include particulate matter from land or river run-off. The third (Figure 29) includes locations that are closer to areas where fishing takes place (i.e., Bay of Plenty, Wairarapa coast, Cook Strait, west coast South Island, western Chatham Rise, and central Campbell Plateau) but offshore enough to avoid the potential complications of particulate matter.

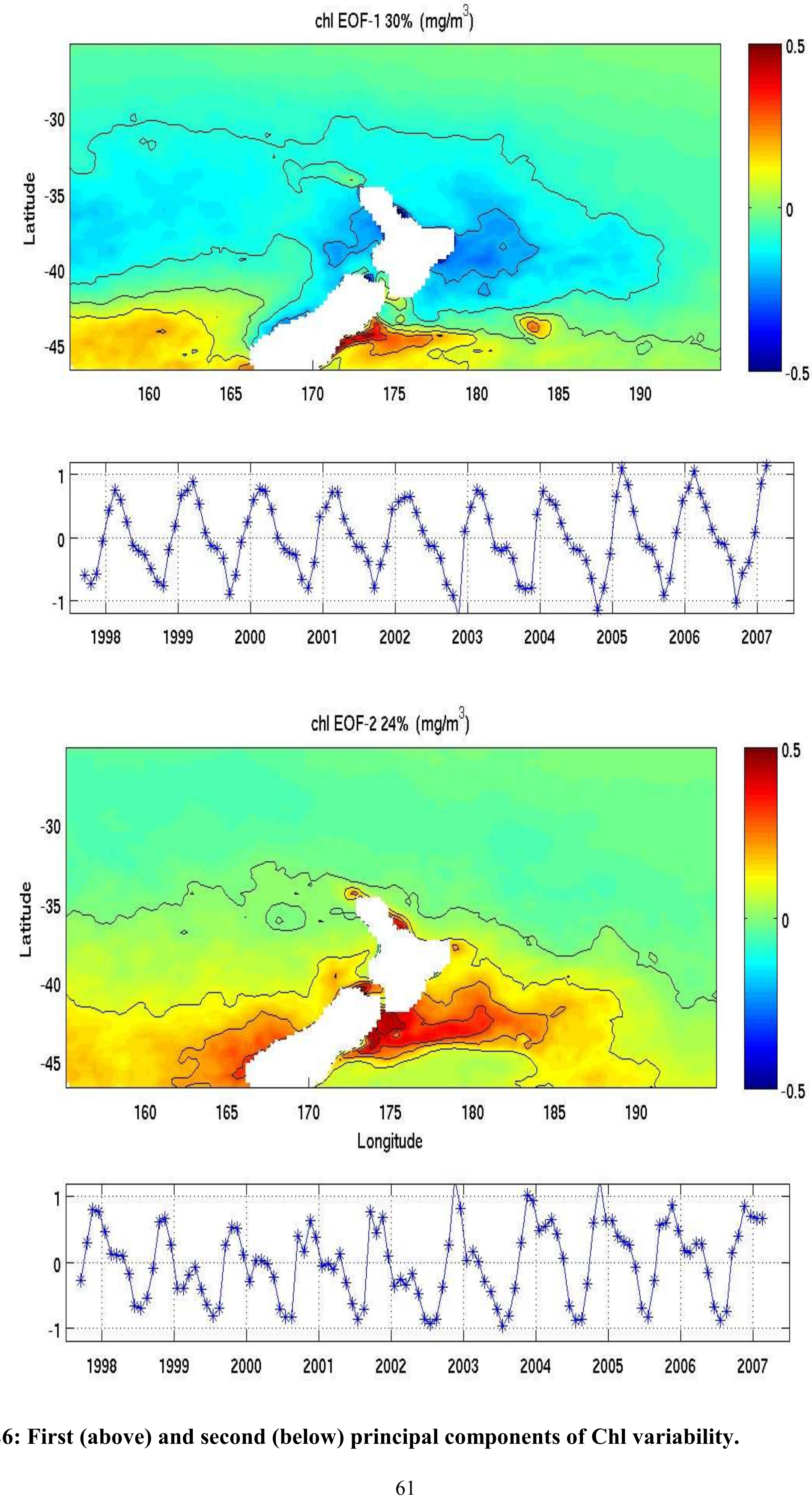


Figure 26: First (above) and second (below) principal components of Chl variability.

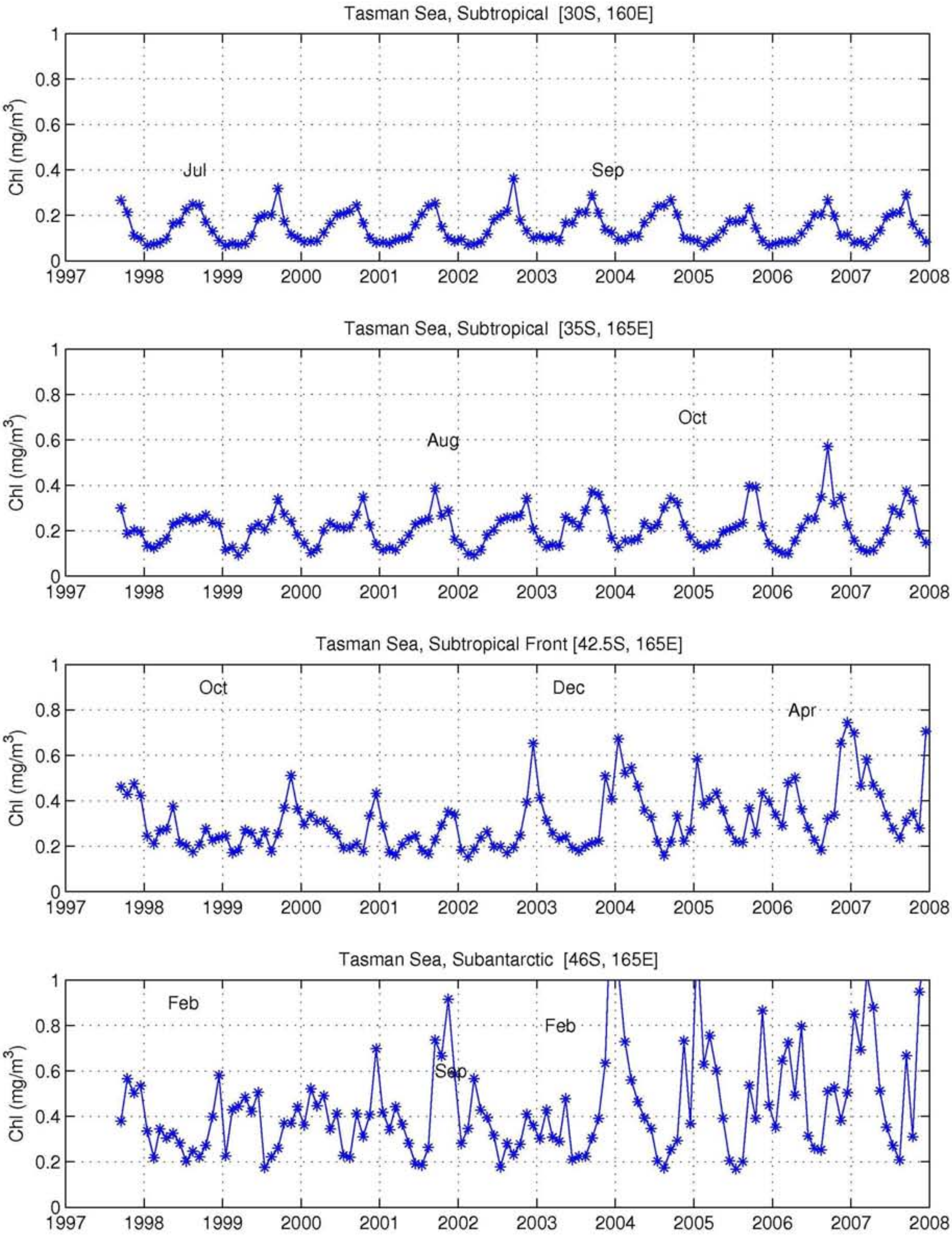


Figure 27: Chl variability along a longitudinal gradient to the west of New Zealand.

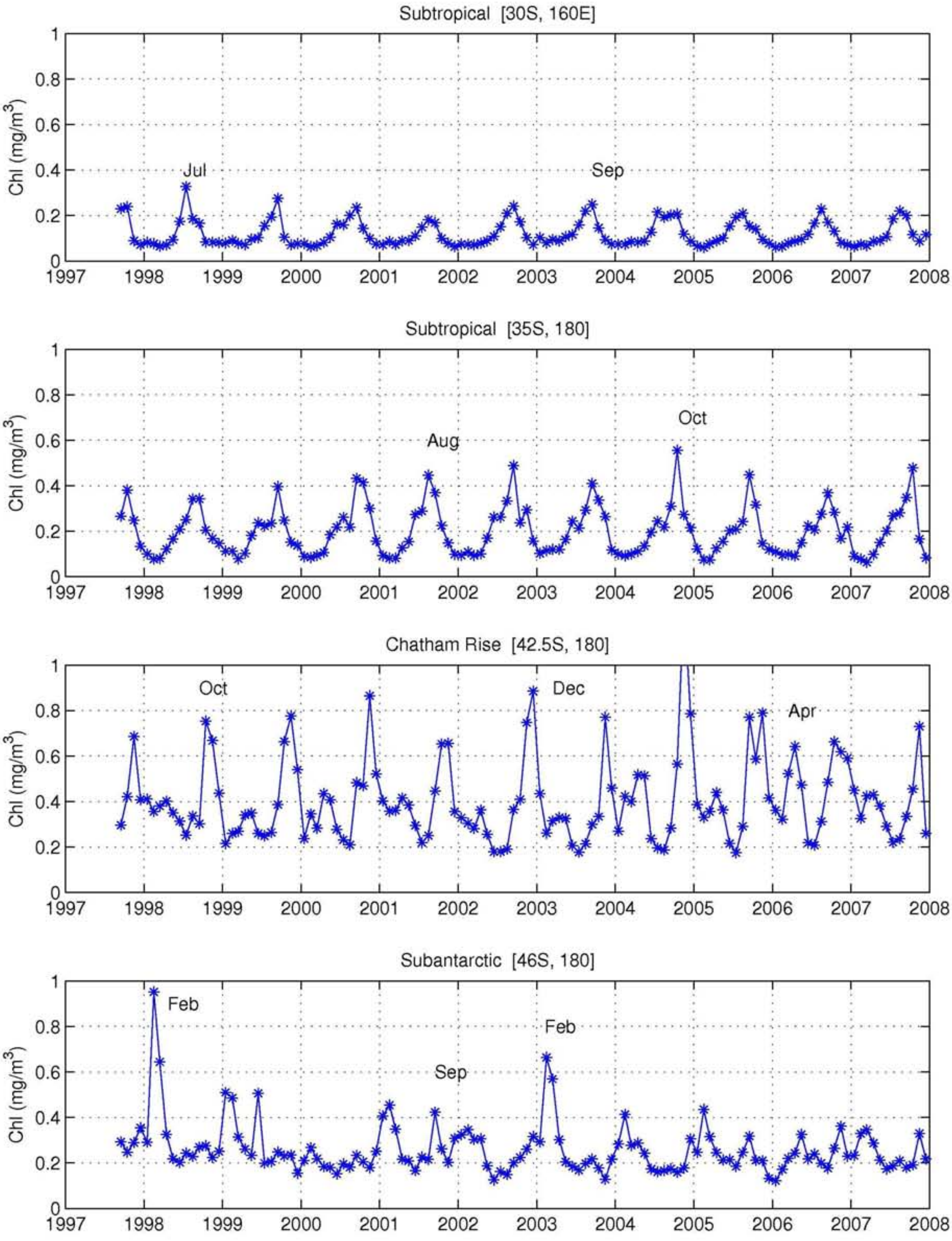


Figure 28: Chl variability along a longitudinal gradient to the east of New Zealand.

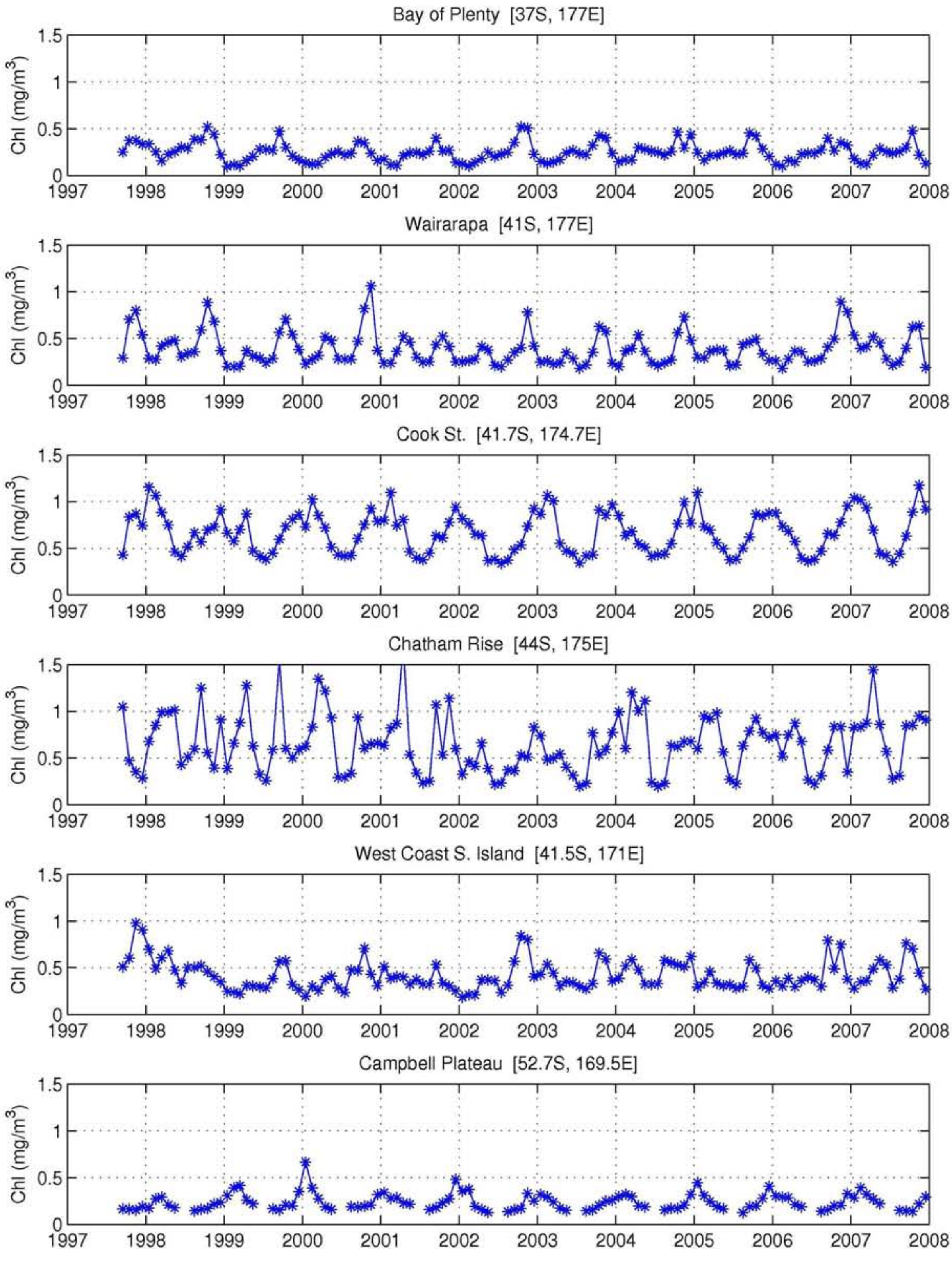


Figure 29: Chl variability at locations of relevance to fisheries operations.

Trends/cycles

In the two series of north-south transects to the east and west of New Zealand, the variability in Chl values is highest (up to about 10-fold) in southern areas (42.5° S and 46° S). Annual cycles with a clear late winter/spring peak occur in the north. Seasonal bimodality is more common in the two southern locations: at 42.5° S there is a larger spring peak in October–December and a secondary autumn peak in April–May; at 46° S, the patterns are less consistent with the dominant peak sometimes in November–February and secondary peaks in autumn. Chlorophyll is consistently higher on the Chatham Rise compared to other locations. The only locations to show clear annual trends over time are on the western transect, at 42.5 and 46° S, where Chl appears to be higher in the last 5–6 years (Figure 29).

Locations closer to fisheries activities show annual peaks occur between September and December off the west coast South Island, the Bay of Plenty and off the Wairarapa, between September and April in Cook Strait, and December and February on the Campbell Plateau. There is no clear annual cycle on the Chatham Rise; there is usually a low in winter, but major peaks occur at differing months from spring through to autumn. Total Chl is highest and occurs over more extended periods in Cook Strait and on the Chatham Rise. Annual Chl in peak seasons varies with no evidence of consistent trends among areas. The clearest annual changes in Chl are from the west coast South Island where spring values were highest in 1997, 2002, 2006, and 2007 and lowest in 1999 and 2001.

Dunn et al. (2009) compared annual mean estimates of Chl for three regions (west coast South I., SubAntarctic and Chatham Rise) with SST for Fisheries Management Areas (FMA) and found some evidence of a positive relationship for the SubAntarctic and FMA 6 (0.64) and the Chatham Rise and FMAs 3 and 4 (0.42, 0.46), but a stronger negative relationship for the west coast South Island and FMA 7 (-0.79). There were also some relatively strong correlations between the regional Chl and SOI, Kidson and Trenberth indices.

In order to achieve greater understanding of how Chl is related to the various climate and oceanographic conditions (particularly winds, SST, and upwelling), and because of the large variability observed in areas such as the Chatham Rise, further development of indices would best be approached on appropriate spatial and temporal scales relevant to specific fisheries, rather than for generalised regions (such as FMAs) or point locations.

3.11 Currents

In New Zealand, the ability to observe ocean currents is improving, but remains relatively limited. Most knowledge of currents over the broad scale has been obtained inferentially via geostrophic current calculations based on satellite observations of sea surface height (SSH) (see Section 8), or from insitu measurements of the ocean density structure using conductivity, temperature depth (CTD)-profilers. The SSH measurements provide estimates of the ‘near-surface’ geostrophic currents, but with the caveat that the observations are spatially relatively sparse. The CTD measurements provide for a depth profile, but tend to be single snapshots. Current meters on sparsely located moorings measure currents insitu, providing time variability but limited vertical profile. Acoustic Doppler Current Profilers (ADCP), either ship-mounted, or moored, can supplement the vertical spatial gaps from current meter moorings, but are also sparsely located.

Numerical models can fill in the gaps in the observing network; however, our ability to validate (and hence have confidence in) our numerical models of ocean currents is constrained and it is therefore difficult to link ocean currents and their variability to fish abundance and distribution. This is also complicated by the differing ability of fish in their various life history stages (e.g., eggs, larvae) to passively drift or actively swim. For passive drifters, currents encountered will change in space and time; underlying eddy fields on top of the mean currents will disperse drifters as they move through the evolving ocean flow. It is this kind of complexity that needs to be addressed when considering the dispersal of passive biological material under the influence of ocean currents.

In order to provide better measurements of passive dispersal, floats in the form of drifters have been routinely placed into the surface ocean under the auspices of the Global Drifter Program. These drifters routinely report their position to satellites, allowing for global estimates of surface ocean currents and their dispersal properties. From this information, better estimates of how well models can capture both the mean and eddy variability of the surface ocean can be made (e.g., see Chiswell & Rickard (2006)).

An example of the information derived from the Global Drifter Program is shown in Figure 30 (figure 2 from Chiswell et al. 2007). It shows mean surface currents obtained from all drifter trajectories that have passed through the New Zealand region. The mean can then be subtracted from the individual drifter flows to obtain an estimate of the insitu eddy characteristics of the surface water in this region. Such data can also be used to validate numerical models of dispersal.

Currents at depth have also been estimated from data obtained from floats of various types. Morris et al. (2001) reported on circulation at around 900 m deep from subsurface floats traversing the subantarctic waters around New Zealand (see their figure 2). More recently, flow trajectories at 1000 m have been derived using Argo float information (see Section 3.8 above). As the number of Argo floats in the global ocean has increased, so the statistical confidence in derived data. The map of mean circulation at 1000 m from Argo floats in Figure 31 is consistent with the derived flow from Morris et al. (2001).

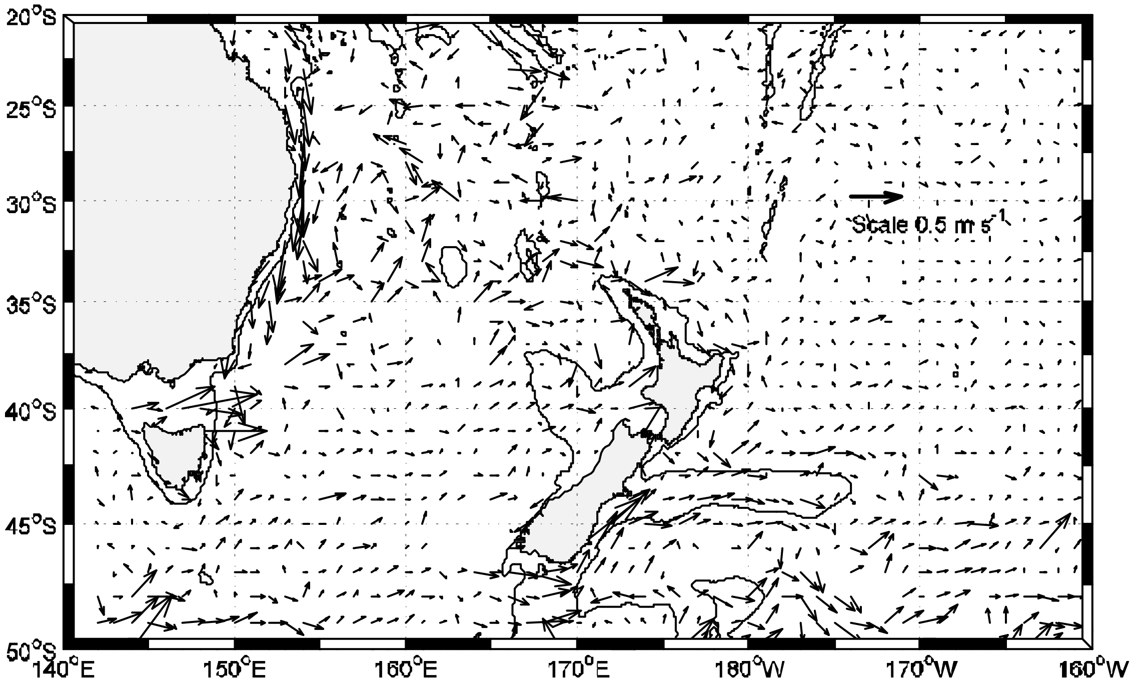


Figure 30: Mean surface velocity field derived from 1° by 1° latitude-longitude binned mean of Global Drifter Program drifter velocities. From Chiswell et al. (2007).

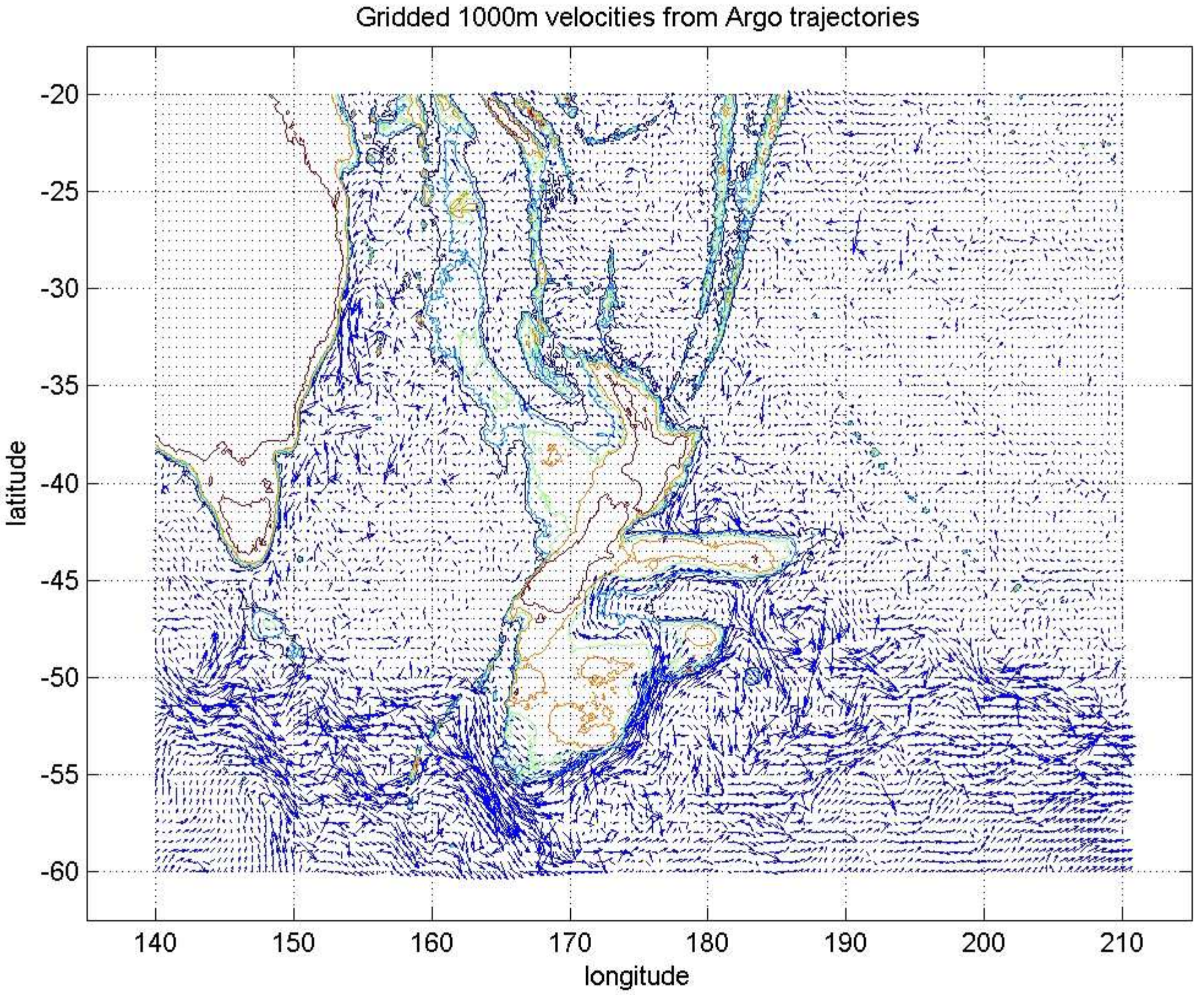


Figure 31: The velocity vectors at 1000m depth calculated from Argo trajectory data, averaged in 0.5° latitude and longitude bins. (P. Sutton, pers. comm.).

Ocean models fill in the gaps in the observing network. The quality of these models depends on the amount of available data (which for the oceans is still relatively sparse) and the resolution of the model relative to the scales of interest. One of the highest resolution operational models for our region comes from an Australian collaboration under the name of 'Bluelink' (see Oke et al. (2008) for details). Figure 32 shows the horizontal spatial grid used by Bluelink; it has global coverage, but with the finest spatial scales (currently 10 km scale) in the Australia-New Zealand region.

The promise of Bluelink in terms of provision of high-resolution maps of currents has to be tempered by on-going work using observations to validate the quality of the output of Bluelink. As the observing network grows denser (as it has to in order to capture the eddy-scales at less than 10 km or so for the ocean), and as the models improve, our confidence in such models will allow for more routine use of their outputs for attempting to understand the interplay between biology and the ocean currents.

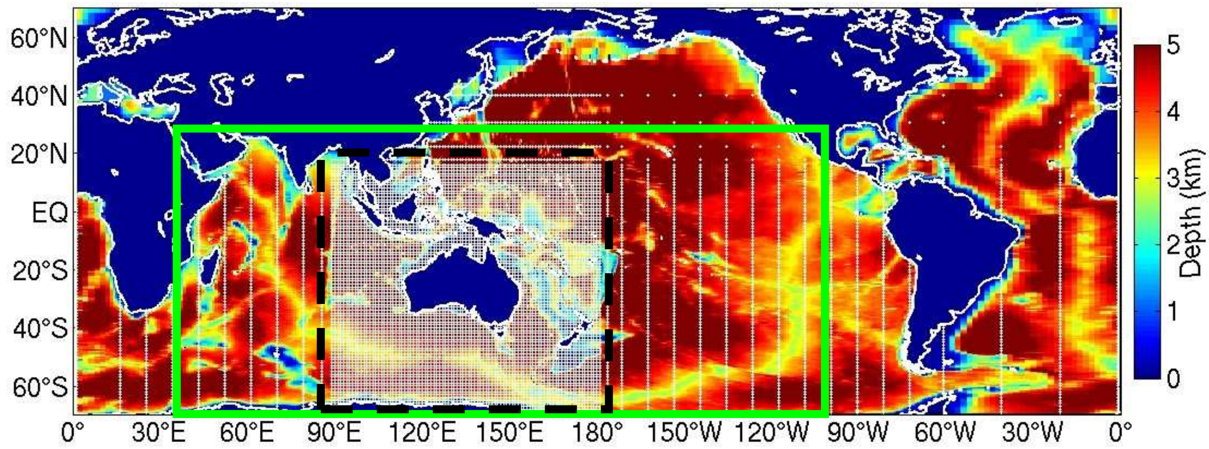


Figure 32: Horizontal resolution grid for the Bluelink operational ocean model. Minimum resolution inside the green border is about 100 km; inside the black border is about 10 km.

A further important issue is that of the coastal zone. Models such as Bluelink rely heavily on the SSH observations for their global coverage. However, in the relatively shallow coastal zones extracting a useable SSH signal becomes difficult. To compound matters, our observing network for the coastal zone is even more limited than for the open ocean; this is not only because satellite observations do not yet help, but also because the competing effects of tides (external and internal), winds, and freshwater forcing (rivers, etc) each make significant contributions to the coastal currents. Typically, to obtain solutions in toward the coastline, higher resolution models are nested inside the open-ocean models and data in the locale of interest have to be used to control the nested solution (if such data exist).

For such an interpolation to a nested model, it is clearly an advantage to have the spatial scales of the outer solution as close as possible to those envisaged for the coastal zone. As an example, consider the surface flow map in Figure 33 which shows annual mean vectors from a regional ocean model run at NIWA. The model has a horizontal resolution of 1/12^{o} (about 7–8 km in our region) and is based on the model in Rickard et al. (2005), and surface validation is provided by Chiswell & Rickard (2006). At the open ocean scale we can see features we might expect for the New Zealand region; to the north we see a model expression of East Cape Eddy, to the east the eddy system comprising the Wairarapa and Hikurangi eddies, and to the south the extension of the Southland Current as it is steered eastwards along the south side of the Chatham Rise.

However, looking more closely at Figure 35, it is apparent that the model is starting to capture some of the finer scale coastal flows. For example, flow through Cook Strait is evident as an extension of flow up the west coast of the South Island. As this flow exits Cook Strait it encounters northward flow from the extension of the Southland Current that passes through Mernoo Gap at the far western end of Chatham Rise. These currents then appear to merge and flow northwards along the eastern side of the North Island; this would appear to be the model representation of the Wairarapa Coastal Current that is known to persist in this area. For comparison, see Hadfield et al. (2007) where a similar NIWA ocean model is validated for fine scale flows over the Chatham Rise region; it is apparent from this work that models at this scale can start to capture a fair degree of the mean and variability seen in the observations.

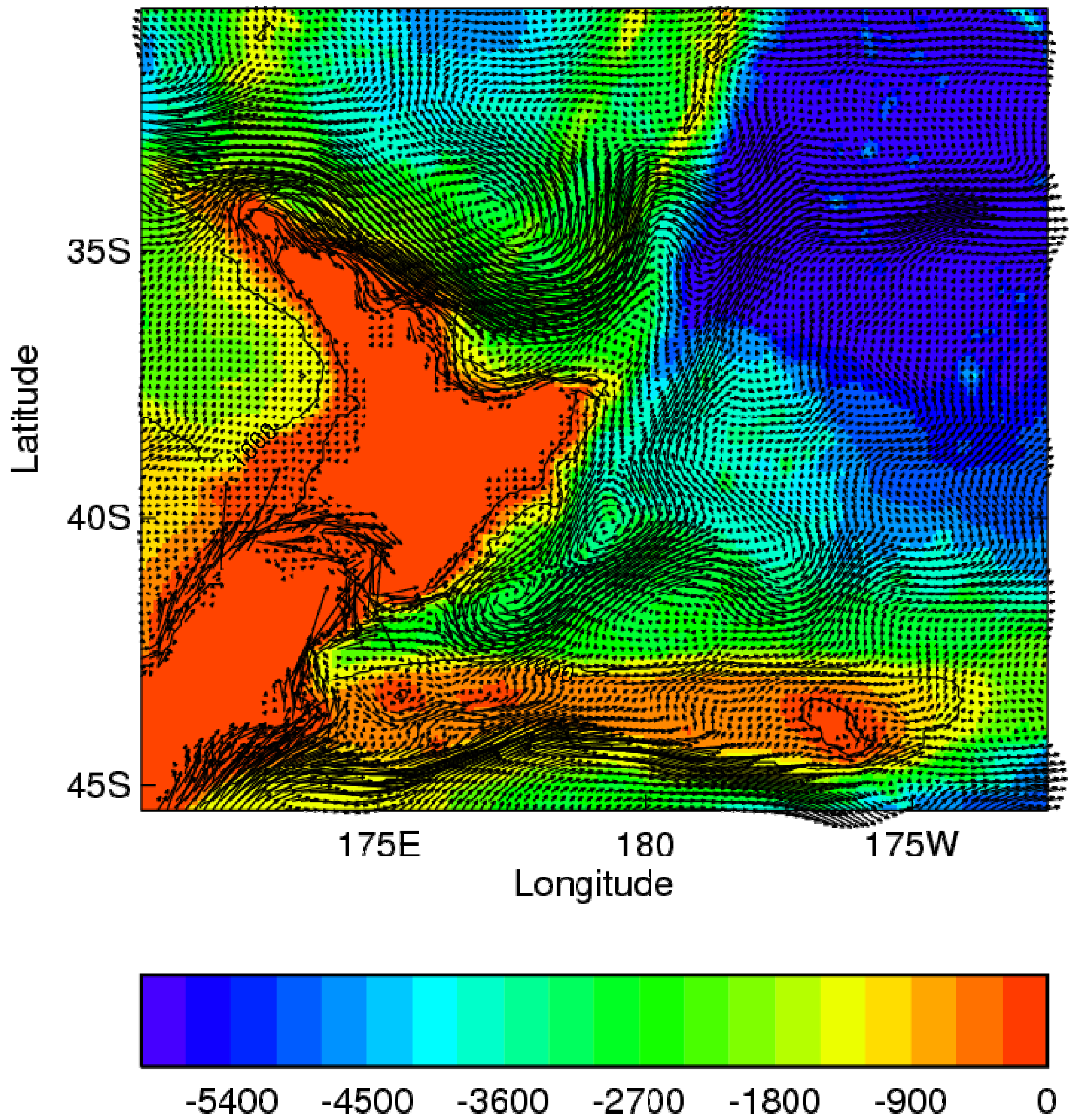


Figure 33: Annual mean surface currents from R25 model (see text) plotted on top of model bathymetry contours. The 100 and 1000 metre isobaths are also shown.

In summary, knowledge of the mean and variability in the currents around New Zealand is slowly improving and operational models are undergoing continuing validation. These improvements will enable better inferences to be made on potential interactions between fisheries and ocean currents. Examples of where such interactions with ocean currents have been investigated include: the retention of rock lobster phyllosoma (mid-stage larvae) in eddy systems (Chiswell & Booth, 1999, 2005, 2007); orange roughy life-history and dispersal (Dunn et al. 2009b); and egg, larval, and juvenile dispersal of toothfish in the Ross Sea area (Hanchet et al. 2008).

3.12 Acidification

3.12.1 Introduction

The increase in atmospheric CO_2 has been paralleled by an increase in carbon dioxide (CO_2) concentrations in the upper ocean (Sabine et al. 2004), with global ocean uptake on the order of 2 gigatonnes (Gt) per annum (about 30% of global anthropogenic emissions, IPCC (2001a)). The anthropogenic CO_2 signal is apparent to an average depth of about 1000 m. Carbon dioxide absorbed by seawater reacts with water to form carbonic acid, the dissociation of which releases hydrogen ions, so raising the acidity (i.e., lowering the pH). The increasing rate of CO_2 input from the atmosphere has surpassed the system's natural buffering capacity and so the surface ocean is becoming more acidic. Since the industrial revolution, ocean pH has decreased by 0.1 units, with a further decrease of 0.4 units to 7.9 predicted by 2100 (Houghton et al. 2001). The pH scale is logarithmic, so a 0.4 pH decrease corresponds to a 300% increase in hydrogen ion concentration. Both the predicted pH in 2100 and the current rate of change in pH are outside the range experienced by the oceans for at least half a million years. Furthermore, this trend may continue, with a decrease to 7.5 by 2300 (Caldeira & Wickett 2003).

Globally, open ocean seawater pH shows relatively low spatial and temporal variability, compared to coastal waters where pH may vary by up to 1 unit in response to precipitation and biological activity in the plankton and sediment. Surface pH in the open ocean has been determined on a monthly basis at time series stations near Bermuda since 1983 (Bates 2001, 2007), and near Hawaii since 1988 (Brix et al. 2004). Both time series records show long term trends of increasing partial pressure of dissolved carbon dioxide in water (pCO_2) and decreasing pH, with the pCO_2 increasing at a rate of 1.25 µatm per year, and pH decreasing by 0.0012 pH units per annum since 1983 at Bermuda,.

In New Zealand, the projected change in surface pH waters between the 1990s and 2070 is a decrease of 0.15-0.18 pH units (Hobday et al. 2006). The only available time series of pH in New Zealand waters is the bimonthly sampling of a transect across neritic, subtropical, and subantarctic waters off the Otago shelf since 1998 (FRST-funded NIWA-University of Otago project). There is no evidence of change in either pCO_2 or pH at present (Figure 34; K. Currie, NIWA pers. comm.), despite a current local atmospheric CO_2 growth rate of 2.1 ppm/year (A. Gomez, NIWA pers. comm.), although this may reflect that the sampling period is too short to distinguish long-term changes from seasonal and interannual variability.

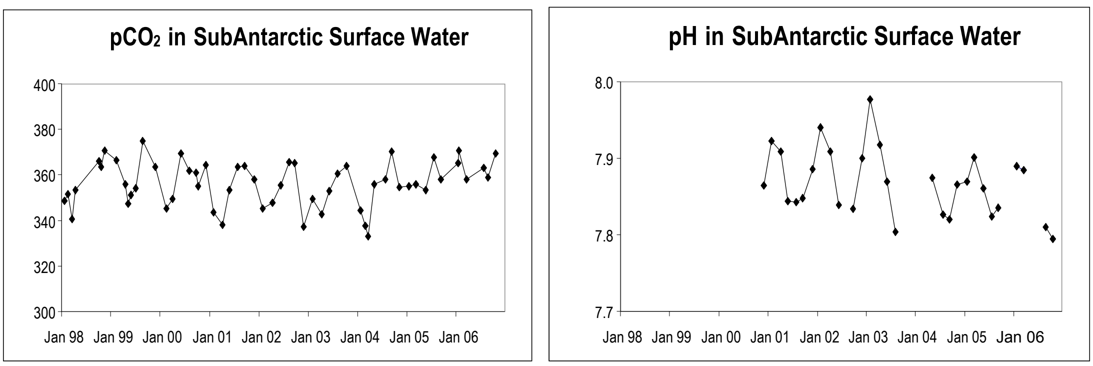


Figure 34: pCO_2 and pH in subantarctic surface seawater from the R.V. *Munida* transect, 1998–2006. The oscillations are primarily due to seasonal changes in water temperature and seasonal effects of biological removal of dissolved carbon in the seawater.

3.12.2 Potential biological impacts

Little research has been carried out to date on potential effects of acidification on New Zealand species, although interest in acidification research has increased recently, for example, the Royal Society of New Zealand acidification workshop in 2009. However, for this report we were reliant on overseas studies. A review by the UK Royal Society has stimulated considerable international research activity on ecosystem and biogeochemical impacts of decreasing pH in the ocean (Royal Society 2009). Primary impacts studied to date can be broadly described in terms of: a reduction in carbonate availability and the impact on organisms that produce shells or body structures of calcium carbonate; stimulation of plankton productivity due to the increasing seawater CO_2 content; and hypercapnia (exposure to high CO_2) leading to acidosis of body fluids and physiological stress.

Reduction in carbonate availability has received most attention to date. The decrease in pH has significant effects on the distribution and concentration of dissolved inorganic carbon (DIC), which is primarily composed of three chemical species: bicarbonate (about 90% of DIC), carbonate (about 10%) and dissolved CO_2 (about 1%). Whereas total DIC is increasing, the balance is shifting towards an increase in bicarbonate and corresponding decrease in carbonate, which is predicted to halve in concentration by 2100 relative to preindustrial levels (Caldeira & Wickett 2005, Orr et al. 2005).

The decreased availability of dissolved calcium carbonate may affect the ability of organisms to build and maintain carbonate skeletons (known as calcification). Under lower temperatures and higher pressure, such as in the deep ocean, carbonate exists only in the dissolved form, whereas at warmer temperatures and lower pressure, calcium carbonate can be maintained in solid structures above the carbonate saturation depth,. The decrease in pH of the surface ocean has caused the saturation depth to shoal, by 50–200 m since the industrial revolution. Consequently calcifying organisms that live in colder waters, such as the polar regions, and/or at depth, are most vulnerable to decreasing pH.

Furthermore, calcium carbonate exists as two polymorphs, calcite and aragonite, of which the aragonite saturation horizon is closer to the surface. Organisms with carbonate shells then differ in their susceptibility to acidification depending on whether they use calcite or aragonite. Projections for aragonite availability in surface waters indicate that saturation has already decreased to 1.0 in Southern Ocean waters, and will become undersaturated by 2050 (Orr et al. 2005). Consequently organisms producing aragonite in colder water are considered the most vulnerable to changes in ocean acidity.

Organisms will be affected by acidification at different levels, from individual physiological responses and competitive fitness through to species and ecosystem impacts, including productivity and community composition, food webs, carbon export, ecosystem functions and services, and the viability and biomass of commercial species. Global calcification will be affected by both reduced calcification rates per individual organism, and by lower abundances of calcifying organisms in marine ecosystems (Tyrrell et.al. 2008). This may alter total particulate inorganic carbon production and also ocean CO_2 uptake, as carbonate formation counter-intuitively increases dissolved CO_2 concentration in surface waters. Consequently a decrease in marine calcification without a concomitant decrease in organic carbon export may lead to increased atmospheric CO_2 drawdown.

Bacteria play an important role in the remineralisation of nutrients and carbon at the base of the food chain, and so influence both plankton productivity (and therefore pelagic foodwebs), and carbon export to the deep ocean. Decreasing pH may negatively impact nitrification by marine bacteria (Huesemann et al. 2002), which is an important source of nitrate that supports phytoplankton growth. Recent measurements in Southern Ocean waters, as part of the New Zealand International Polar Year Ross Sea voyage, confirmed increased bacterial enzyme activity at elevated (750 and 1000 ppmv) CO_2 (E. Maas, NIWA, pers. comm.). These results suggest that particle degradation may be more rapid and carbon export correspondingly lower in a higher CO_2 world, although the impact of more rapid recycling on food webs and fisheries is currently unclear.

Foramanifera are protozoa that form calcium carbonate tests and are found in all marine environments, mainly in the surface euphotic zone. Their role in the food chain is uncertain, but they are major contributors to the transport of carbonate into the deep ocean, with foraminiferal calcite accounting for 32–80% of the total 1.1 Gt calcium carbonate exported (Schiebel 2002).

Coccolithophores are phytoplankton of the Prymnesiophyte group that dominate in subpolar and warmer waters and form massive blooms clearly visible from space, with the most ubiquitous coccolithophore species, *Emiliana huxleyi*, producing 1 million tonnes of calcite globally. Their role in the food chain is uncertain, but they are significant contributors to carbonate export to the deep ocean, supplying up to 38% of the global calcite budget (Schiebel 2002). Initial laboratory and mesocosm studies of two species have shown a decrease in calcification and quality of the liths that make up their outer layer as waters become more acidic (Riebesell et al. 2000, Engel et al. 2005).

Natural populations also showed calcification decreases of 38–83% with increasing CO_2 (Zonderaven et al. 2001, De Lille et al. 2005). However, subsequent studies have shown variability in the response of other species to increasing CO_2 (Langer et al. 2006), indicating that there is no linear relationship between ambient CO_2 and carbonate production within the same group of organisms.

Coccolithophores also fix carbon to form particulate organic carbon (POC), and so contribute to both the vertical export of both carbonate and POC. Coccolithophores have shown potential to respond to elevated CO_2 by increasing photosynthesis and so carbon fixation (e.g., studies by Riebesell et al. 2000, Zondervan et al. 2001, Rost & Riebesell, 2004) although other studies have observed no change (De Lille 2005, Langer et al. 2006). Other phytoplankton groups such as the diatoms have more advanced carbon capture systems and their photosynthetic rate is already saturated at current CO_2 levels.

Non-calcifying phytoplankton productivity appeared to show relatively minor responses to increased CO_2 concentration (Tortell et al. 2002, Engel et al. 2005). Riebesell et al. (2007) showed that dissolved inorganic carbon consumption by a natural plankton community increased with rising CO_2, thereby elevating organic carbon loss from the upper layer, suggesting a more efficient biological carbon pump.

Nitrogen fixing cyanobacteria are found in subtropical waters in nitrogen-limited waters north of New Zealand. A number of recent studies suggest nitrogen fixation by cyanobacteria will increase significantly with increasing CO_2 (Hutchins et al. 2007, Ramos et al. 2007), resulting in potential increased new nitrogen supply that may support phytoplankton productivity and carbon export.

Macroalgae fix carbon from dissolved CO_2 and/or bicarbonate, and so lower pH has the potential to affect metabolism and growth rates. Coralline algae are a major calcifying component of the marine benthos from tropical to polar oceans at all depths in almost every habitat type. They provide key ecological roles in nearshore ecosystems such as benthic habitat and substrate for a diversity of organisms; for example, they may cover up to 80% of rock in coastal Otago, and release chemicals that trigger the settlement of planktonic larvae of paua and kina (C. Hurd, Otago Univsersity, pers. comm). On coral reefs, they function as framework organisms, cementing carbonate fragments into massive reef structures, providing chemical settlement cues for reef-building coral larvae and as major producers of carbonate sediments (Kuffner et al. 2008). Under high CO_2, coralline algae recruitment rate and percentage cover decreased significantly by 78% and 92%, respectively, whereas non-calcifying algae conversely increased by 52% relative to controls, indicating that coralline algae will be less competitive in a high-CO_2 environment resulting in loss of habitat (Beardall et al. 1998).

Corals. The impact of increasing CO_2, and other factors associated with climate change, on warm-water corals has been well studied (see review by Hoegh-Guldburg et al., (2007). Most significantly it has been estimated that global coral carbonate production may decrease by 9–30% by 2050–2100 (Kleypas et al. 1999; Gattuso et al. 1999), with recent estimates of a 1–80% decline in coral calcification in response to a doubling of atmospheric pCO_2 (Langdon & Atkinson 2005).

The New Zealand EEZ does not support warm-water corals but has a diverse cold water coral fauna, primarily framework-forming stony corals (Scleractinia), several of which are found in shallow waters (D. Tracey, NIWA, pers. comm.). Cold water corals provide essential fish habitat, providing shelter, feeding grounds, spawning grounds, nursery areas, and also function as 'stepping stones' for long range dispersal between regions. They are long-lived, slow-growing and susceptible to physical disturbance, with extremely slow rates of recovery. These ecosystems have evolved in highly stable conditions and are therefore likely to be impacted by climate change (Guinotte et al. 2006).

Scleractinian groups deposit calcium carbonate and their distribution is related to the depth of the aragonite saturation horizon (Guinotte et al. 2006). As aragonite saturation in high latitude waters is already low due to colder temperatures, disappearance of cold water corals from deeper areas is predicted. Studies suggest that these corals may survive acidification, but decalcification may result in major structural and functional changes of coral reef ecosystems (Fine & Tchernov, 2007).

Zooplankton. The main focus of acidification impact studies on zooplankton has been on the pteropods, filter-feeding zooplankton that live primarily in the upper few hundred metres. Pteropods are important components of Southern Ocean and subantarctic Pacific Ocean foodwebs, and contribute to the diet of carnivorous zooplankton, myctophid and other fishes, baleen whales, and form the entire diet of gymnosome molluscs. They replace krill as the dominant zooplankton in the Ross Sea, and represent a large proportion of the annual export flux of both carbonate and organic carbon in some regions of the Southern Ocean. They form aragonitic shells, which will be difficult to maintain in the cold polar regions; for example, experiments on *Clio pyrimidata* at 788 ppm CO_2 identified rapid dissolution and significant shell deterioration within 48 hours (Orr et al. 2005). As they will be unable to maintain their protective shell in a more corrosive ocean, pteropod populations are likely to decline, and their range contract towards lower-latitude surface waters that remain supersaturated in aragonite, with impacts on Southern Ocean fisheries, productivity, and carbon export.

Soft bottom communities. Changes in pH will change the composition and nature of the sediment itself, as a large fraction of the sediment is calcium carbonate in origin, thereby modifying the habitat and causing indirect impacts on soft sediment biota. This may particularly affect burrowing organisms that are sensitive to sediment type, and impact on the higher food chain.

Echinoderms are keystone species that control kelp distributions and are fished extensively worldwide. Evidence indicates that larval settlement and recruitment in sea urchins is susceptible at lower pH (Kurihara & Shirayama 2004), as production of the outer test is affected during the larval settlement stage at high pCO_2. Under lower pH the fertilisation rate of eggs of intertidal echinoderms declined, and larvae were severely malformed (Kurihara & Shirayama 2004).

Molluscs perform a wide variety of ecosystem functions including bioturbation, food source, and habitat modifiers. There are many mollusc species around New Zealand with important roles in maintaining ecosystem diversity and function (cockles, pipi, paua, green lipped mussel), that are also economically important, with high commercial value and are reared using aquaculture.

Oysters may be less sensitive to changes in pH as their shells are calcite, whereas mussel shells are mostly aragonite. Some studies have shown that elevated CO_2 negatively affects the metabolic efficiency and growth rates of mussel and oysters (Michaelidis et al. 2005, Gazeau et al 2007), whereas experiments of greater duration (45 days) have shown no significant difference in mussel growth at pH 7.4–7.6 to that at 8.1 (Berge et al. 2006). The impact of acidification on bivalve productivity may be significant and has potential ramifications for the future viability of shellfish aquaculture. The Pacific oyster was the most cultivated species globally in 2002, with a total volume of 4.2 million t (10.8% of total world aquaculture production) and global mussel production of 1.4 million t (Gazeau et al. 2007). Currently in New Zealand, total revenue estimates for green-lipped mussel aquaculture is $181 million and for Pacific oysters (North Island) is $26 million (Source: www.fish.govt.nz).

Cephalopods and pelagic fish. Elevated dissolved CO_2 will result in increased absorption, potentially resulting in acidosis of the blood and a decrease the oxygen-carrying capacity, although species are likely to respond differently (Ishimatsu et al. 2004). In general, long-term steady-state elevations in CO_2 levels may be tolerated by organisms with a low activity mode of life or pre-adapted to large fluctuations in environmental parameters. Studies of pelagic species suggests sensitivity may be maximal in ommastrephid squid, which are characterised by a high metabolic rate and extremely pH-sensitive blood oxygen transport, whereas sensitivity is lower in fish with lower metabolic rates, intracellular blood pigments, and capacity to compensate for CO_2 induced acid-base disturbances (Portner et al. 2004). In squid and high-activity pelagic fish, acidosis may reduce growth and reproduction, with long-term effects at the population level and ramifications for ecosystems, food webs, and commercial interests. In the last 5 years, the New Zealand arrow squid fishery has caught 36 000 to 71 000 tonnes annually at a value of $68−172 millions (www.fish.govt.nz).

Indirect effects, via disruption at lower trophic levels (zooplankton and phytoplankton), or sensitivity of larval stages, may have more significant impacts on top predators. For example, a regime shift in the Bering Sea between 1996 and 2000 (Merico et al. 2003) saw a decrease in diatoms and increase in the coccolithophores, which resulted in a significant decline in regional salmon catch.

Summary

The maintenance of existing, and development of new, pH time series surveys in New Zealand waters is critical. The variation in response to acidification between and within species of the same groups highlights the need for studies of New Zealand indigenous species, not reliance on predictions from overseas studies. The most vulnerable species may be cold-water calcifying organisms that use aragonite, such as pteropods and cold-water corals, because carbonate under-saturation will occur at an earlier stage in colder Southern Ocean and Sub-Antarctic waters. Squid and pelagic fish species, which are adapted to constantly low CO_2 levels, may also be more sensitive to change in CO_2; larval and juvenile stages, particularly of calcifying groups, are also vulnerable.

Potential positive impacts of acidification include increased phytoplankton carbon fixation and export, and increased productivity of subtropical waters due to enhanced nitrogen fixation by cyanobacteria.

Responses of susceptible organisms to acidification may include adaptation (though on timescales beyond anything experienced in at least 500 000 years); distributional shifts (by area or depth) for more mobile groups; and physiological stress, resulting in reduced growth rates, fecundity, and tolerance to predation and disease, and increased likelihood of replacement by more tolerant species, with implications for food webs and ecosystem structure.

4. DISCUSSION

The indices presented in this report vary in terms of spatial and temporal scales; some are more appropriate in terms of specific locations (e.g., upwelling, air temperature, and coastal SST), some are more appropriate on a regional or a New Zealand wide basis (e.g., synoptic weather patterns, SST); some may be important on shorter time scales (e.g., synoptic weather patterns, Chl, SST) while others are more important over annual or even decadal timescales (e.g., SOI, IPO). There have been some attempts to correlated trends over similar time and spatial scales, where appropriate, but limited correlative studies across disciplines (i.e., atmospheric with ocean variables). Some series of indices are new and require ongoing research and development, including consideration of how they relate to other ocean climate variables (e.g., the relation of upwelling indices to wind stress; ocean colour to SST, SSH, and wind patterns). Other potentially important aspects such as current variability and acidification are only just starting to be modelled or monitored.

Some general observations on recent trends in some of the key ocean climate indices that have been found to be correlated with a variety of fisheries processes (including recruitment fluctuations, growth, distribution, productivity, and catch rates) are as follows.

- The Interdecadal Pacific Oscillation (IPO, or PDO): available from 1900; time scale 10–30 years. The IPO has been found to have been correlated with decadal changes ('regime shifts') in Northeast Pacific ecosystems (e.g., Alaska salmon catches). In the New Zealand region, there is evidence of a regime shift into the negative phase of the IPO in about 2000. During the positive phase, from in the late 1970s to 2000, New Zealand experienced periods of enhanced westerlies, with associated cooler air and sea temperatures and enhanced upwelling on western coasts. Opposite patterns are expected under a negative phase. For most New Zealand fisheries, monitoring of changes in populations began in the late 1970s, so we have no information on how our fisheries might respond to these longer-term climatic fluctuations. Some of the recent changes in fish populations since the mid 1990s, for example, low western stock hoki recruitment indices (Francis 2009) and increases in some elasmobranch abundance indices (Dunn et al. 2009a), may be shorter-term fluctuations that might be related in some way to regional warming during the period (see Section 3.8) and only longer-term monitoring will establish whether they might be longer-term ecosystem changes.

- The Southern Oscillation Index: available from 1900; best represented as annual means. Causal relationships of correlations of SOI with fisheries processes are poorly understood but are probably related in some way to one or more of the underlying ocean climate processes such as winds or temperatures. When the index is strongly negative, an El Niño event is taking place and New Zealand tends to experience increased westerly and southwesterly winds, cooler sea surface temperatures, and enhanced upwelling in some areas (see, for example, the correlation of Leigh monthly SST and SOI indices). This has been found to be related to increased nutrient flux and phytoplankton growth in areas such as the west coast South Island, Pelorus Sound, and northeast coast of the North Island (Willis et al. 2007a, Zeldis et al. 2008). El Niño events are likely to occur on 3–7 year time scales and are likely to be less frequent during the negative phase of the IPO which began in about 2000. This is likely to impact positively on species that show stronger recruitment under increased temperature regimes (e.g., snapper, Francis 1993, 1994a, 1994b).

- Surface wind and pressure patterns: available starting from 1940s or 1960s; variation in patterns can be high over monthly and annual time scales and many of the indices are correlated with each other, and with SOI and IPO indices (e.g., more zonal westerly winds, more frequent or regular cycles in southerlies in the positive IPO, 1977–2000). Correlations with fisheries process may occur over short time scales (e.g., affecting fish catchability) as well as seasonal and annual scales (e.g., affecting recruitment success). Wind and pressure patterns have been found to be correlated with fisheries indices for southern gemfish (Renwick et al. 1998), hake, red cod, and red gurnard (Dunn et al. 2009a), rock lobster (Booth et al. 2000), and southern blue whiting (Willis et al. 2007b, Hanchet & Renwick, 1999). Causal relationships of these correlations are poorly understood but can be factored into hypothesis testing as wind and pressure patterns affect surface ocean conditions through heat flux, upwelling, and nutrient availability on exposed coasts.

- Temperature and sea surface height: available at least monthly over long time scales (air temperatures from 1906) or relatively short time scales (ocean temperatures to 800 m, SST, and

SSH variously from 1987). Ocean temperatures, SST, and SSH are all correlated with each other and smoothed air temperatures correlate well with SST in terms of interannual and seasonal variability; there are also some correlations of SST and SSH with surface wind and pressure patterns (see Dunn et al. 2009a). SST has been found to be correlated with fisheries indices for elephantfish, southern gemfish, hoki, red cod, red gurnard, school shark, snapper (also air temperatures), stargazer 2001 and tarakihi (Francis 1994a, 1994b, Renwick et al 1998, Beentjes & Renwick 2001, Gilbert & Taylor 2001, Dunn et al 2009a). Air temperatures have increased since 1900; most of the increase occurred since the mid 1950s. Increases from the late 1970s to 2000 may have been moderated by the positive phase of the IPO. Coastal SST records from 1954 (Portobello) also show a slight increase through the series and, in general, show strong correlations with SOI (i.e., cooler temperatures in El Niño years). Other time series (SSH, ocean temperature to 800 m) are comparatively short but show cycles of warmer and cooler periods on 1–6 year time scales. All air and ocean temperature series show the significant warming event during the late 1990s which has been followed by some cooling, but not to the levels of the early 1990s.

- Ocean colour and upwelling: these will be important time series to monitor for the future because they potentially have a more direct link to fisheries process and are more easily incorporated into hypothesis testing. At this stage they require more detailed development and analysis. The ocean colour series starts in late 1997, so is not able to track changes that may have occurred since before the late 1990s warming cycle. These indices also need to be analysed with respect to SST, SSH, and wind patterns, at similar locations or on similar spatial scales. The upwelling indices require more validation, in particular, by correlation with along-shore wind stress and currents. The preliminary series developed here exhibit some important spatial differences and trends that warrant further investigation in relation to fisheries indices. Of note are the increased Chl indices off the west and southwest coasts of the South Island in spring/summer during the last 5–6 years and the relatively low upwelling indices off the west coast South Island during winter in the late 1990s.

- Currents: there are no general indices of trends or variability at present. Improvements in monitoring technology (e.g., satellite observations of SSH, CTD, ADCP, Argo floats) have resulted in more information becoming available to enable numerical models of ocean currents to be developed. On the open ocean scale, there is considerable complexity in the New Zealand zone (e.g., frontal systems, eddy systems of the east coast). In the coastal zone, this is further complicated in coastal areas by the effects of tides, winds, and freshwater (river) forcing, and a more limited monitoring capability. Nevertheless, the importance of current systems is starting to become more recognised and incorporated into analysis and modelling of fisheries processes and trends. Recent examples include the retention of rock lobster phyllosoma (mid-stage larvae) in eddy systems (Chiswell & Booth 2005, 2007), the apparent bounding of orange roughy nursery grounds by the presence of a cold-water front (Dunn et al. 2009b), and the drift of toothfish eggs and larvae (Hanchet et al. 2008).

- Acidification: The increase in atmospheric CO_2 has been paralleled by an increase in CO_2 concentrations in the upper ocean, resulting in a decrease in pH. Maintenance of the one existing New Zealand monitoring program for pH and pCO_2, and development of new programmes to monitor the impacts of pH on key groups of organisms are critical. Potentially vulnerable groups include organisms that produce shells or body structures of calcium carbonate (corals, molluscs, plankton, coralline algae), and also non-calcifying groups including plankton, squid and high-activity pelagic fishes. Potentially positive effects of acidification include increased phytoplankton carbon fixation and vertical export and increased productivity of subtropical waters due to enhanced nitrogen fixation by cyanobacteria. Secondary effects at the ecosystem level, such as productivity, biomass, community composition, and biogeochemical feedbacks, also need to be considered.

Climate change was not specifically addressed as part of this report, although indices described here are an integral part of monitoring the speed and impacts of global warming. As noted under the air temperature section (Section 3.4), the slightly increasing trend in temperatures since the 1950s is likely to have been moderated by the positive phase of the IPO, from the late 1970s to the late 1990s. With the shift to a negative phase of the IPO in 2000, it is likely that temperatures will increase more steeply. Continued monitoring of the ocean environment and response is critical. This includes not only the impacts on productivity, at all levels, but also on increasing ocean acidification.

5. MANAGEMENT IMPLICATIONS

Most of the ocean climate trends described are either nationwide (e.g., IPO, SOI) or show similar trends across the EEZ (air temperatures, coastal SST, SST, ocean temperatures to 800 m depth, and SSH by FMA). Their influence on fisheries and marine ecosystems may therefore be relatively widespread. Trends in some other indices are more variable by location (e.g., ocean colour, upwelling, finer scale SST) or may have different expression in different locations (e.g., surface wind and pressure patterns) that will influence fisheries and ecosystems on finer scales.

Internationally, ocean climate variables are increasingly being found to be important in driving fisheries processes, from localised short-term effects on catchability (e.g., storm events) to seasonal variations potentially affecting recruitment (e.g., temperature and snapper) and longer-term global changes (e.g., regime shifts, global warming) potentially affecting current systems, fish distribution, and abundance and ocean acidification.

In New Zealand, many of the time series of fisheries indices are relatively short. Catch histories for some key inshore species go back to the 1930s, but many of the deeper water species were not caught in low numbers until the 1970s. All of the atmospheric indices (air temperature, wind and pressure patterns) span these time scales, but the ocean indices such as ocean temperatures to 800 m, SST, SSH, ocean colour, and upwelling are all relatively recent, mostly available only from the 1990s. Most of these time series are too short to enable robust correlative studies of the type carried out on hoki by Francis et al. (2006). As all of these time series increase in length or are further developed, better correlative studies will be possible, assuming that appropriate fisheries monitoring series are maintained and further developed. For ocean acidification, there is a need to develop new series to start to monitor effects into the future.

The potential to use such correlative studies to predict potential effects of regime shifts and climate change on fisheries will depend not only on more robust correlative studies, but on more research and understanding of causal relationships. Even then, ecosystems are inherently changing and adaptable, and predictions based on the past may have limited relevance for the future. For example, a meta-analysis of the success of published environment–recruitment correlations when tested with new data showed verification upon retest was low (Myers 1998), except for populations at the limit of a species' geographical range. Myers suggested that future progress would require testing general hypotheses using data from many populations.

For the New Zealand region, key ocean climate drivers in the last decade have been:

- the significant warming event in the late 1990s
- the regime shift to the negative phase of the IPO in about 2000, which is likely to result in fewer El Niño events, i.e., fewer zonal westerly winds (already apparent compared to the 1980–2000 period) and increased temperatures; this is the first regime shift to occur since most of our fisheries monitoring time series have started (the previous shift was in the late 1970s), and
- global trends of increasing air and sea temperatures and ocean acidification.

On more localised scales, these general trends may be more or less pronounced or variable and there can be local differences likely to be important for fish distribution, recruitment, and growth. For example, the increase in SSH indices in the late 1990s was more pronounced in northern and western FMAs (1,7, 8, 9); patterns in SST appear less variable in the SubAntarctic and, while all series show the late 1990s warming, there are regional differences in other highs and lows; and productivity is greater in mid-latitudes and annual variability is higher on the Chatham Rise and lowest in Cook Strait.

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APPENDIX 1: Glossary of climatic or oceanographic terms

Sources: **W** (Wikipedia: http://en.wikipedia.org/wiki/)
BB (Boxed brain: http://ipmf2007.org/)
AMS (American Meterological Society: : http://amsglossary.allenpress.com/glossary/)
Baum (Glossary of Physical Oceanography and Related Disciplines, Steven K. Baum, 2004: http://stommel.tamu.edu/~baum/paleo/ocean/ocean.html)
Note: Some of these sources provide more detailed information than that given here.

Aerosol: A colloidal system in which the dispersed phase is composed of either solid or liquid particles, and in which the dispersion medium is some gas, usually air (e.g., haze, most smokes, and some fogs and clouds may thus be regarded as aerosols). (AMS: http://amsglossary.allenpress.com/glossary/search?p=1&query=Aerosol&submit=Search)

Anticyclone**:** a weather phenomenon in which there is a descending movement of the air and a high pressure area over the part of the planet's surface affected by it. Anticyclonic flow spirals in a clockwise direction in the northern hemisphere and counter-clockwise in the southern (W: http://en.wikipedia.org/wiki/Anticyclone)

Blocking anticyclone: An anticyclone that remains nearly stationary for a week or more at middle to high latitudes, so that it blocks the normal eastward progression of high- and low-pressure systems. (Baede 2007)

Carbon pump: The name given to the cycling of $CaCO_3$ in the ocean. Plants and animals living in the euphotic zone have $CaCO_3$ skeletons (tests) which they precipitate from dissolved calcium and carbonate ions. The $CaCO_3$ formed this way eventually sinks and is dissolved back to calcium and carbonate ions in the deeper parts of the water column and in the sediments. The ocean circulation closes the loop by transporting the ions back to the surface waters. This pump creates a surface depletion and a deep enrichment of both dissolved inorganic carbon (DIC) and alkalinity. An increase in the strength of this pump will serve to increase atmospheric CO_2 since the pump variations have twice as great an effect on alkalinity as on DIC. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node7.html#DIC)

Carbon sink: A reservoir that receives carbon from another carbon reservoir. Commonly used to denote a reservoir where the carbon amount increases because its total carbon received from all other reservoirs exceeds its total carbon transfer to the other reservoirs. (AMS: http://amsglossary.allenpress.com/glossary/search?p=1&query=carbon+sink&submit=Search)

Depression**:** A depression is an area of low pressure usually bringing unsettled weather. A deepening depression has a lowering of pressure at its centre. The profile of a depression would read as follows: 'a warm front bringing a wide belt of layered clouds with steady rain. It will be followed by a cold front bringing first showers then brighter more settled weather. In the warm sector between the two fronts we can expect quite dull weather broken by storms.' (BB: http://ipmf2007.org/weather-depression/)

East Australian current: The western boundary current of the southern hemisphere in the Pacific Ocean. It is the weakest of the world's boundary currents, carrying about 15 Sv in the annual mean near 30º N, yet is also associated with strong current instabilities. The relative weakness is due mostly to the flow through the Australasian Mediterranean Sea and the instabilities probably result from the current following the coast and then suddenly separating somewhere near 34º S to follow the east coast of New Zealand (where it is known as the East Auckland Current). It is stronger and reaches further inshore during the summer, with flow speeds reaching 1 m/s during the summer, and the maximum transport has been estimated at around 30 Sv (although the intermittent nature of the current makes such estimates somewhat suspect). (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node9.html)

El Niño–Southern Oscillation (ENSO): El Niño is a term originally applied as a description of an annual weak warm current running southward along the coast of Peru and Ecuador during the Christmas holiday, i.e., the Spanish word for ``the boy Christ-child" is Niño. The name El Niño eventually became associated with unusually large warmings that occur every few years and effect large changes on the local, regional, and even global climate. It gradually became known that the coastal warming was part of a much larger warming of the upper waters of the Pacific extending as far as the international date line. There is an associated atmospheric phenomenon called the Southern Oscillation, with the combined changes in atmosphere and ocean termed El Niño/Southern Oscillation or ENSO, with El Niño properly referring to the warm phase of ENSO. A typical El Niño event begins in the nothern spring or sometimes summer, peaks from November to January in SSTs, and ends the following summer. The opposite phase is similarly called La Niña, i.e. Spanish for ``the girl,'' and features a basinwide cooling in the tropical Pacific. The entire system is called El Niño in many if not most popular accounts. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node9.html). Note that in the New Zealand region, the climate effects are opposite to that described here; El Niño refers to the cool phase of ENSO.

Empircal Orthogonal function: In statistics and signal processing, the method of empirical orthogonal function (EOF) analysis is a decomposition of a signal or data set in terms of orthogonal basis functions which are determined from the data. It is the same as performing a principal components analysis on the data, except that the EOF method finds both time series and spatial patterns. (W: http://search.live.com/results.aspx?q=empiracle+othagonal+function&src=IE-SearchBox)

Eulerian: In oceanography, the time-averaged flow field in a fixed coordinate system. This can be remarkably different from the synoptic mean circulation. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node10.html)

Expendable bathythermograph (XBT): An expendable instrument that is dropped from a vessel and used to measure the profile of temperature in the water column. The probe consists of a thermistor in a weighted, streamlined case. It falls freely at a fixed, known rate so that the elapsed time can be converted to depth. It is connected by a thin, freely unwinding wire to a small buoy with a radio transmitter through which the data are transmitted to the vessel, which continues its journey. (AMS modified: http://amsglossary.allenpress.com/glossary/search?p=1&query=Expendable+bathythermograph+&submit=Search)

geostrophic balance: describes a balance between Coriolis and horizontal pressure-gradient forces (AMS: http://amsglossary.allenpress.com/glossary/search?id=geostrophic-balance1)

Geostrophic winds or currents: A wind or current that is in balance with the horizontal pressure gradient and the Coriolis force, and thus is outside of the influence of friction. Thus, the wind or current is directly parallel to isobars and its speed is inversely proportional to the spacing of the isobaric contours. (Baede 2007)

Interdecadal Pacific Oscillation (IPO)**:** Pacific-wide reorganisation of the heat content of the upper ocean, representing large scale decadal temperature variability (Salinger et al. 2001, Folland et al. 2002)

Isotherm: A type of contour line connecting points of equal temperature.

La Niña: the name for the cold phase of ENSO, during which the cold pool in the eastern Pacific intensifies and the trade winds strengthen. (W: http://en.wikipedia.org/wiki/La_Nina#La_Ni.C3.B1a)

Mixed layer depth: In oceanography, a nearly isothermal surface layer of around 40 to 150 m depth caused by wind stirring and convection. Brainerd & Gregg (1995) defined this as ``the envelope of maximum depths reached by the mixing layer on time scales of a day or more, i.e., the zone that has been mixed in the recent past. It generally corresponds to the zone above the top of the seasonal pycnocline.'' In the winter, low surface temperatures and large waves (with their accompanying turbulent mixing) can deepen the mixed layer all the way to the permanent thermocline. Higher temperatures and a less energetic wave climate in the summer can lead to the development of a seasonal thermocline at the base of the mixed layer that overlies the permanent thermocline. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node24.html)

Ocean acidification: A decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide.

pCO_2**:** the partial pressure of dissolved carbon dioxide in water

Pacific Decadal Oscillation (PDO): see Interdecadal Pacific Oscillation (IPO

Polarity**:** May be applied to any property of a physical system that can take on only two values, usually opposite in some sense (e.g., sign or direction). (AMS: http://amsglossary.allenpress.com/glossary/search?p=1&query=Polarity&submit=Search)

Regime shifts: infrequent, large changes in oceanic conditions that spread through the food web. Depending on dynamics of the ecosystem, the response of a biological organism to some external forcing can be smooth, abrupt, or discontinuous. Regime shifts can occur, for example, when changes in ocean conditions, such as warming, affect plankton production, an event that easily propagates up the food chain. Changes in ocean conditions can also affect migration patterns, growth rates, and mortality of fish species. (http://www.innovations-report.com/html/reports/earth_sciences/report-28654.html)

Southern Annular Mode: Preferred patterns of change in atmospheric circulation corresponding to changes in the zonally averaged midlatitude westerlies. The Northern Annular Mode has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation. The Southern Annular Mode occurs in the southern hemisphere. The variability of the mid-latitude westerlies has also been known as zonal flow (or wind) vacillation, and defined through a zonal index. (Baede 2007)

Southern Oscillation Index (SOI): An index that is calculated to monitor the ENSO phenomenon. It is defined as the pressure anomaly at Tahiti minus the pressure anomaly at Darwin, Australia. Anomalously high pressure at Darwin and low pressure at Tahiti are indicative of El Nino conditions. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node36.html)

Subtropical front (STF): In physical oceanography, a region of pronounced meridional gradients in surface properties that serves as the boundary between the Southern Ocean and the waters of the subtropical regime to the north. This was originally called the Subtropical Convergence (DTC) by Deacon but the newer terminology arose in the mid 1980s. This is generally a subduction region for various types of Central Water. The STF separates the Subantarctic Surface Water to the south from the Subtropical Surface Water to the north. The surface hydrographic properties of the STF include a rapid salinity change from 35.0 to 34.5 and a strong temperature gradient (from 14–10 C in winter and 18–14 C in summer) as one crosses from north to south. At 100 m its approximate location is within a band across which temperatures increase northward from 10 to 12 C and salinities from 34.6 to 35.0, with the salinity gradient usually the more reliable indicator. The position as well as the intensity of sinking or rising motion in the STF is more variable than in any other front or divergence in the Southern Ocean. (Baum: http://stommel.tamu.edu/~baum/paleo/ocean/node36.html)

Synoptic weather types: classification of synoptic weather patterns into discriminate groups through statistical analysis (e.g., cluster analysis, Kidson (2000); principal components analysis) (http://faculty.dwc.edu/Slater_John/CR_2005.pdf)

Thermocline: a thin but distinct layer in a large body of water, such as an ocean or lake, in which temperature changes more rapidly with depth than it does in the layers above or below. In the ocean, the thermocline may be thought of as a invisible blanket which separates the upper mixed layer from the calm deep water below. (W: http://search.live.com/results.aspx?q=thermocline&go=&form=QBRE)

Trade winds: The wind system, occupying most of the tropics, that blows from the subtropical highs toward the equatorial trough; a major component of the general circulation of the atmosphere. The winds are northeasterly in the northern hemisphere and southeasterly in the southern hemisphere. In the northern hemisphere they begin as north-northeast winds at about latitude 30° N in January and latitude 35° N in July, gradually veering to northeast and east-northeast as they approach the equator. Their southern limit is a few degrees north of the equator. The southeast trades occupy a comparable region in the southern hemisphere and similarly change from south-southeast on their poleward side to southeast near the equator. In the Pacific, the trade winds are properly developed only in the eastern half of that ocean. They are characterised by great constancy of direction and, to a lesser degree, speed; the trades are the most consistent wind system on earth. (AMS abbreviated: http://amsglossary.allenpress.com/glossary/search?p=1&query=trade+winds&submit=Search

***Westerly wind belt*: westerlies:** (Also called circumpolar westerlies, circumpolar whirl, countertrades, middle-latitude westerlies, polar westerlies, subpolar westerlies, subtropical westerlies, temperate westerlies, zonal westerlies, westerly belt, zonal winds.) Specifically, the dominant west-to-east motion of the atmosphere, centered over the middle latitudes of both hemispheres (on average, from about 35° to 65° latitude). (http://amsglossary.allenpress.com/glossary/search?id=westerlies1)