8. New Zealand Climate and Oceanic Setting

Scope of chapter	Overview of primary productivity, oceanography, bentho-pelagic coupling and oceanic climate trends in the SW Pacific region.
Area covered	New Zealand regional setting
Focal localities	Pan New Zealand waters
Key issues	• Climate and oceanographic variability and change are of relevance to fisheries and the broader marine environment • Allows for improved understanding of the links between observed patterns and drivers of biological processes.
Emerging issues	• New Zealand's oceanic climate is changing • Causal mechanisms that link the dynamics of a variable marine environment to variation in biological productivity, particularly of fisheries, are not well understood in New Zealand. • Need for improved understanding of the linkages between the pelagic and benthic environment (i.e., bentho-pelagic coupling). • The cumulative effects of ocean climate change and other anthropogenic stressors on aquatic ecosystems (productivity, structure and function) are likely to be high. • Some long-term trends in the marine environment are available at a national scale but are not reported. Growing recognition that stressors will act individually & interactively, confounding prediction of net effects of climate change
MPI Research (current)	Projects include ZBD2005-05: Long-term effects of climate variation and human impacts on the structure and functioning of New Zealand shelf ecosystems; ZBD2008-11 Predicting plankton biodiversity & productivity with ocean acidification; ZBD2009-13. Ocean acidification impact on key NZ molluscs; ZBD2010-40. Marine Environmental Monitoring Programme; ZBD2010-41 Deepsea fisheries habitat and ocean acidification.
NZ Research (current)	NIWA Coast & Oceans Centre, Climate Centre; University of Otago-NIWA shelf carbonate geochemistry & bryozoans; Munida time-series transect; Geomarine Services-foraminiferal record of human impact; Regional Council monitoring programmes; Statistics New Zealand Environmental Domain review.
Links to Fisheries 2030 and MPI's Our Strategy	Environmental Outcome Objective 1; environmental principles of Fisheries 2030; MPI's "Our Strategy 2030": two key stated focuses are to maximise export opportunities and improve sector productivity; increase sustainable resource use, and protect from biological risk.
Related issues and/or Chapters	• Ocean related climate variability and change are predicted to have major implications for fishstock distributions and abundance, reproductive success, ecosystem goods and services, deepsea coral habitat and Habitats of Particular Significance to Fisheries Management, • A significant warming event occurred in the late 1990s • A regime shift to the negative phase of the IPO occurred in about 2000,

	which is likely to result in fewer El Niño events for a 20–30 year period, i.e., less 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 will likely impact on fish productivity • New Zealand trends of increasing air and sea temperatures and ocean acidification are consistent with global trends.

8.1. *Context*

Climate and oceanographic conditions play an important role in driving the productivity of our oceans and the abundance and distribution of our fishstocks, and hence fisheries. A full analysis of trends in climate and oceanographic variables in New Zealand is given in Hurst *et al.* (2012) and is now being developed as an Ocean Climate Change Atlas for New Zealand waters (Boyd and Law.2011).

New Zealand is essentially part of a large submerged continent (Figure 8.1).

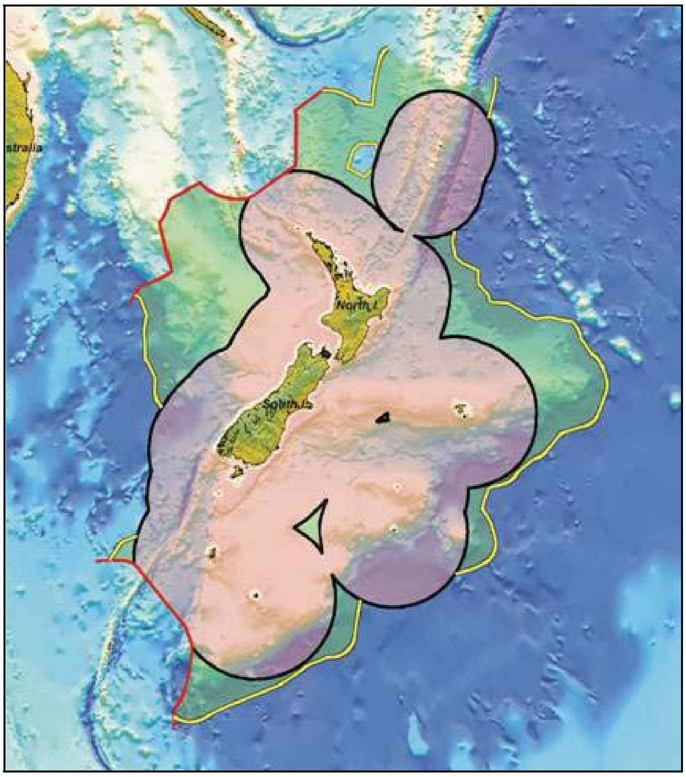

Figure 8.1: New Zealand land mass area 250,000 km^2; EEZ & territorial sea area (pink) 4,200,000 km^2; extended continental shelf extension area (light green) 1,700,000 km^2; Total area of marine jurisdiction 5,900,000 km^2. The black line shows the boundary of the New Zealand EEZ, the yellow line indicates the extension to New Zealand's legal continental shelf, and the red line the agreed Australia/New Zealand boundary under UNCLOS Article 76. Image courtesy of GNS.

The territorial sea (TS extending from mean low water shore line to 12 nautical miles) and Exclusive Economic Zone (the EEZ, extending from 12 nautical miles to 200 miles offshore) and the extended continental shelf (ECS) combine to produce one of the largest areas of marine jurisdiction in the world, an area of almost 6 million square kilometres, (Figure 8.1). New Zealand waters straddle more than 25 degrees of latitude from 30º S in warm subtropical waters to 56º S in cooler, subantarctic waters, and 28 degrees of longitude from 161º E in the Tasman Sea to 171º W in the west Pacific Ocean. New Zealand's coastline, with its numerous embayments, is also long, with estimates ranging from 15,000 to 18,000 km, depending on the method used for measurement (Gordon *et al.* 2010).

New Zealand lies across an active subduction zone in the western Pacific plate, tectonic activity and volcanism have resulted in a diverse and varied seascape within the EEZ. The undersea topography comprises a relatively narrow band of continental shelf down to 200 m water depth, extensive continental slope areas from 200 to 1000 m, extensive abyssal plains, submarine canyons and deep sea trenches, ridge systems and numerous seamounts and other underwater topographic features such as hills and knolls. There are three significant submarine plateaus, the Challenger Plateau, the Campbell Plateau in the subantarctic, and the Chatham Rise (Figure 8.2).

Disturbance of current flow across the plateaus and around the New Zealand landmass gives rise to higher ocean productivity than might be expected, given New Zealand's isolated location in the generally oligotrophic western Pacific Ocean (Figure 8.3). Higher ocean colour, reflecting higher levels of productivity, is typically found around the coast and to the east across the Chatham Rise (Figure 8.3; Pinkerton *et al.* 2005). The coastal waters and plateaus support a range of commercial shellfish and finfish fisheries from the shoreline to depths of about 1500 m. Seamounts, seamount chains and ridge structures in suitable depths provide additional localized areas of upwelling and increased productivity sometimes associated with commercial fisheries.

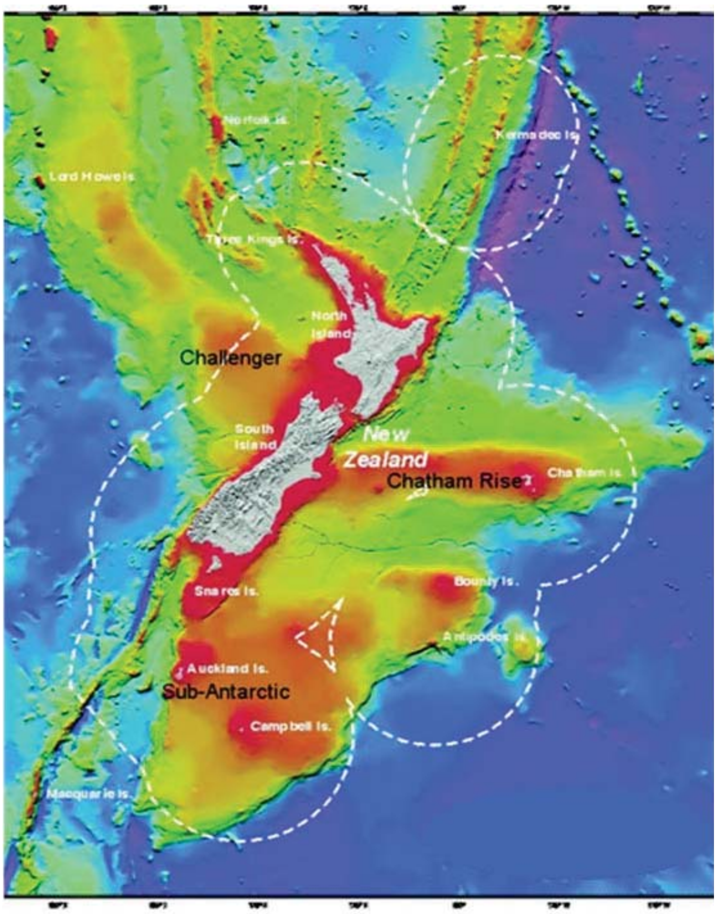

Figure 8.2 Undersea topography of New Zealand (red shallow to blue deep). White dash line shows the EEZ boundary. Image courtesy of NIWA.

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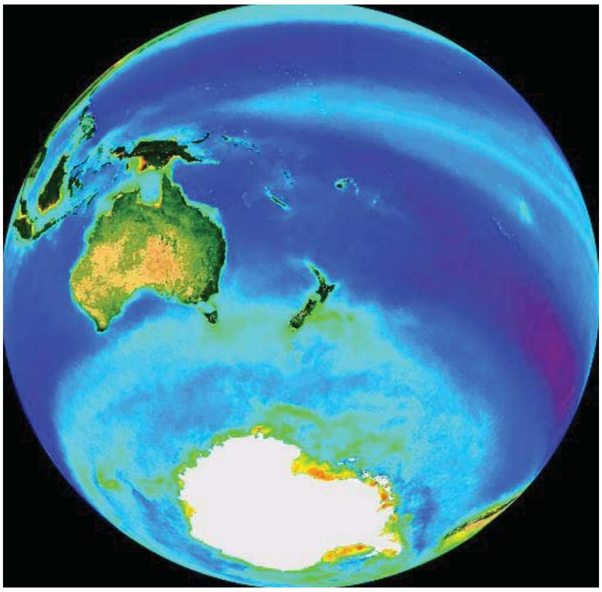

Figure 8.3: SeaWIFS image showing elevated chlorophyll a (green) near New Zealand. Image courtesy of NOAA

Both Figures 8.3 and 8.4 (left panel) show that the strongest chlorophyll *a* and ocean colour are associated with the coastal shelf around New Zealand and the Chatham Rise. Although remote sensing cannot readily distinguish between primary productivity (from phytoplankton) and sediments in freshwater runoff, so interpretation of the relative productivity levels inshore has to be made in conjunction with knowledge of river flow, it is clear that the Chatham Rise has the highest productivity levels in the region. Globally, New Zealand net primary productivity levels in the sea are higher compared with most of Australasia, but lower than most coastal upwelling systems around the world (Willis *et al.*, 2007).

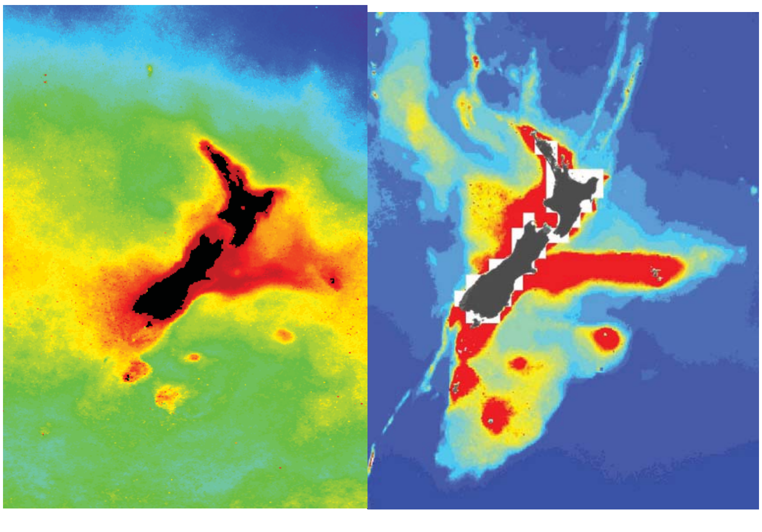

Figure 8.4: Left panel: Ocean colour in the New Zealand region from satellite imagery. Red shows the highest intensity of ocean colour typically associated with higher primary productivity. Right panel: The relative concentrations of particulate organic carbon (POC) that reach the seafloor. Red shows the highest levels, which are likely to be associated with areas of enhanced benthic productivity (based on the model of Lutz *et al.* (2007)). Images courtesy of NIWA.

Patterns in surface waters of primary productivity are mirrored to an extent in the amount of "energy" that sinks to the seafloor (Figure 8.4). This POC flux is based on a model which accounts for sinking rates of dead organisms and predation in the water column (Lutz *et al.* 2007). This is a potential surrogate of benthic production, and indicates where bentho-pelagic coupling may be strong. Highest levels of POC flux match with surface productivity to a large extent, with coastal waters (including around the offshore islands) and the Chatham Rise having high estimated production.

The Tasman Sea (west of New Zealand) is separated from the South Pacific Gyre by the New Zealand landmass (Figure 8.5). The South Pacific Western Boundary Current, the East Australian Current (EAC) flows down the east coast of Australia, before separating from the Australian landmass in a variable eddy field at about 31 or 32°S (Ridgway & Dunn 2003). The bulk of the separated flow crosses the Tasman Sea as the Tasman Front (Stanton 1981; Ridgway & Dunn 2003), before a portion of the flow attaches to New Zealand, flowing down the northeast coast as the East Auckland Current (Stanton *et al.* 1997). In the southern limit of the Tasman Sea is the Subtropical Front, which passes south of Tasmania and approaches New Zealand at the latitude of Fiordland (Stanton 1988), before diverting southward around New Zealand, and then northward up the southeast coast of New Zealand where it is locally called the Southland Front (Heath 1985; Chiswell 1996; Sutton 2003).

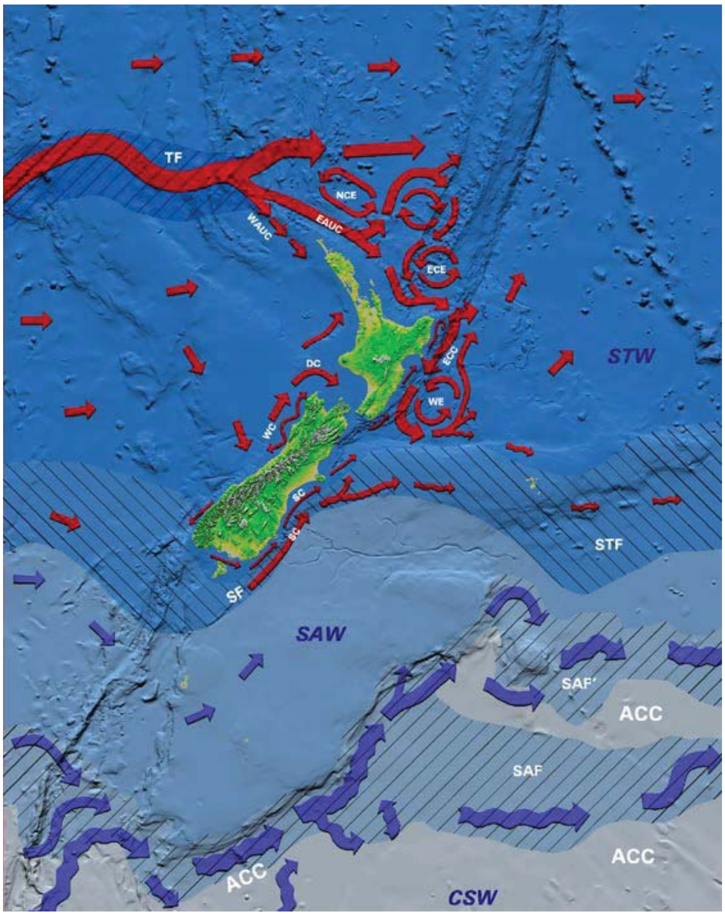

Figure 8.5: Circulation around New Zealand. TF Tasman Front (large red arrows), WAUC West Auckland Current, EAUC East Auckland Current, NCE North Cape Eddy, ECE East Cape Eddy, ECC East Cape Current, WE Wairarapa Eddy, DC D'Urville Current, WC Westland Current, SC Southland Current, SF Southland Front, STW Subtropical Water, STF Subtropical Front (left diagonal hashed area), SAW Subantarctic Water, SAF Subantarctic Front (right diagonal hashed area), ACC Antarctic Circum-Polar Current, CSW Circum-Polar Surface Water, DWBC Deep Western Boundary Current (large purple arrows) (after Carter *et al.* 1998).

The water in the eastern central Tasman Sea south of the Tasman Front, east of the influence of the EAC and north of the Subtropical Front is thought to be relatively quiescent. Ridgway & Dunne (2003) show eastward surface flow across the interior of the Tasman Sea sourced from the southernmost limit of the EAC, with the flow bifurcating around Challenger Plateau and, ultimately, New Zealand. Reid's (1986) analysis indicates that a small anticyclonic gyre exists in the western Tasman Sea at 1000–2500 m depth. This gyre is centred at about 35°S, 155°E on the offshore side of the EAC and west of Challenger Plateau. All indications are that the eastern Tasman region overlying Challenger Plateau is not very energetic.

This is in contrast with the east coast of both the North and South Islands, and Cook Strait, which are highly energetic. Campbell Plateau waters are well mixed though nutrient limited (iron), leading to tight coupling between trophic levels (Bradford-Grieve *et al.* 2003). The Subtropical Front lies along the Chatham Rise and turbulence and upwelling results in relatively high primary productivity in the area.

8.2. *Indicators and trends*

8.2.1. Sea temperature

Sea surface temperature (SST), sea surface height (SSH), air temperature and ocean temperature to 800m depth, all exhibit some correlation with each other over seasonal and inter-annual time scales (Hurst *et al.* 2012). Air temperatures have increased by about 1°C since 1900 (Figure 8.6).

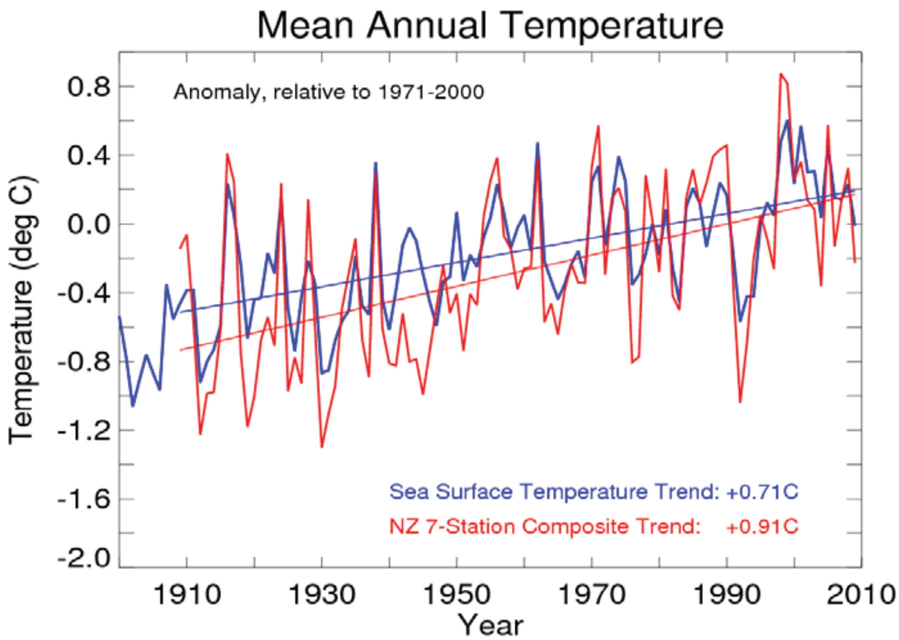

Figure 8.6: Annual time series in New Zealand. NOAA annual mean sea surface temperatures (blue line)[25] and NIWA's seven-station annual mean air temperature composite series (red line), expressed as anomalies relative to the 1971-2000 climatological average. Linear trends over the period 1909-2009, in °C/century, are noted under the graph. (Image Source Mullan *et al.* 2010)

Although a linear trend has been fitted to the seven-station temperatures in Figure 8.6, the variations in temperature over time are not completely uniform. For example, a markedly large warming occurred through the periods 1940-1960 and 1990-2010. These higher frequency variations can be related to fluctuations in the prevailing north-south airflow across New Zealand (Mullan *et al.* 2010). Temperatures are higher in years with stronger northerly flow, and are lower in years with stronger southerly flow. One would expect this, since southerly flow transports cool air from the Southern Oceans up over New Zealand

[25] http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php

The unusually steep warming in the 1940-1960 period is paralleled by an unusually large increase in northerly flow during this same period Mullan *et al.* (2010). On a longer timeframe, there has been a trend towards less northerly flow (more southerly) since about 1960 Mullan *et al.* (2010). However, New Zealand temperatures have continued to increase over this time, albeit at a reduced rate compared with earlier in the 20^{th} century. This is consistent with a warming of the whole region of the southwest Pacific within which New Zealand is situated (Mullan *et al.* 2010).

Mullan *et al.* 2010 describe the pattern of warming in New Zealand as consistent with changes in sea surface temperature and prevailing winds. Their review shows enhanced rates of warming (in units of °C/decade) down the Australian coast and to the east of the North Island, and much lower rates of warming south and east of the South Island (Figure 8.7).

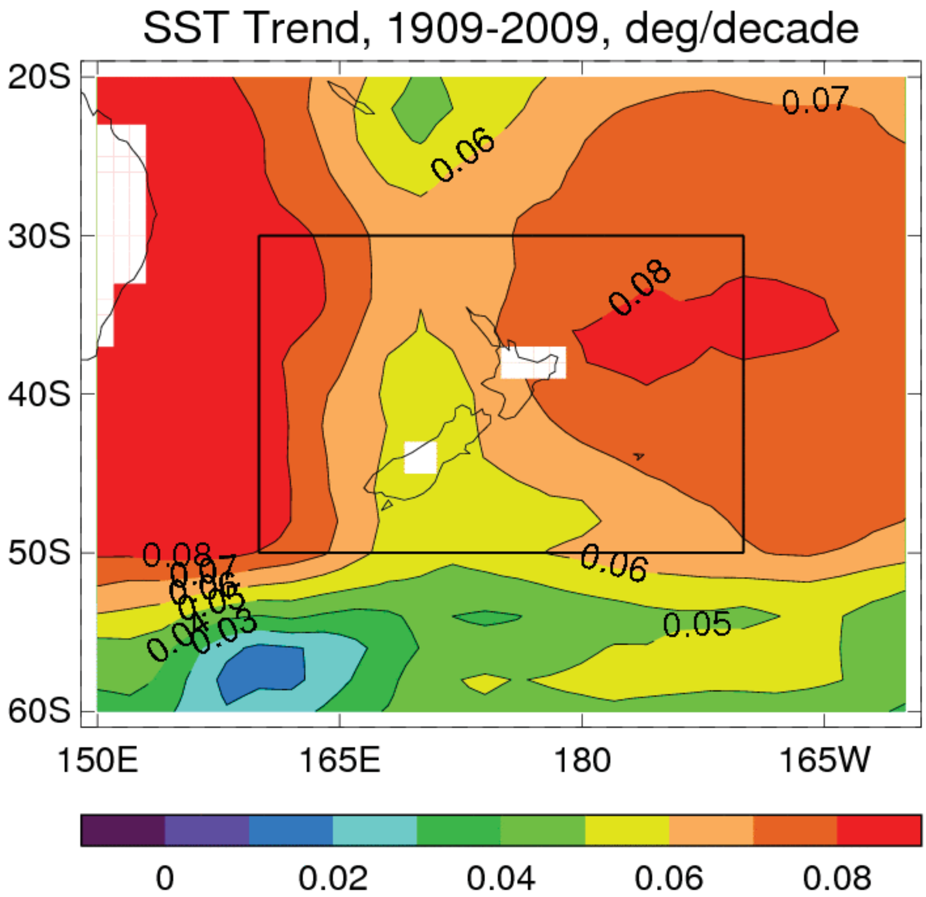

Figure 8.7: Trends in sea surface temperature, in °C/decade over the period 1909-2009, calculated from the NOAA_ERSST_v3 data-set (provided by NOAA's ESRL Physical Sciences Division, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/). The data values are on a 2° latitude-longitude grid. The box around New Zealand denotes the region used to produce the area-averaged sea temperatures plotted in Figure 2. (Image Source Mullan *et al.* 2010.)

Figure 8.8 gives a broader spatial picture at much higher resolution (but a shorter period, since 1982). It is apparent that sea temperatures are increasing north of about 45°S; they are increasing more slowly, and actually decreasing in recent decades, off the Otago coast and south of New Zealand. This regional pattern of cooling (or only slow warming) to the south, and strong warming in the Tasman and western Pacific can be related to increasing westerly winds and their effect on ocean circulation Mullan *et al.* (2010). Thompson and Solomon (2002) discuss the increase in Southern Hemisphere westerlies and the relationship to global warming; Roemmich *et al.* (2007) describe recent ocean circulation changes; Thompson *et al.* (2009) discuss the consequent effect on sea surface temperatures in the Tasman Sea.

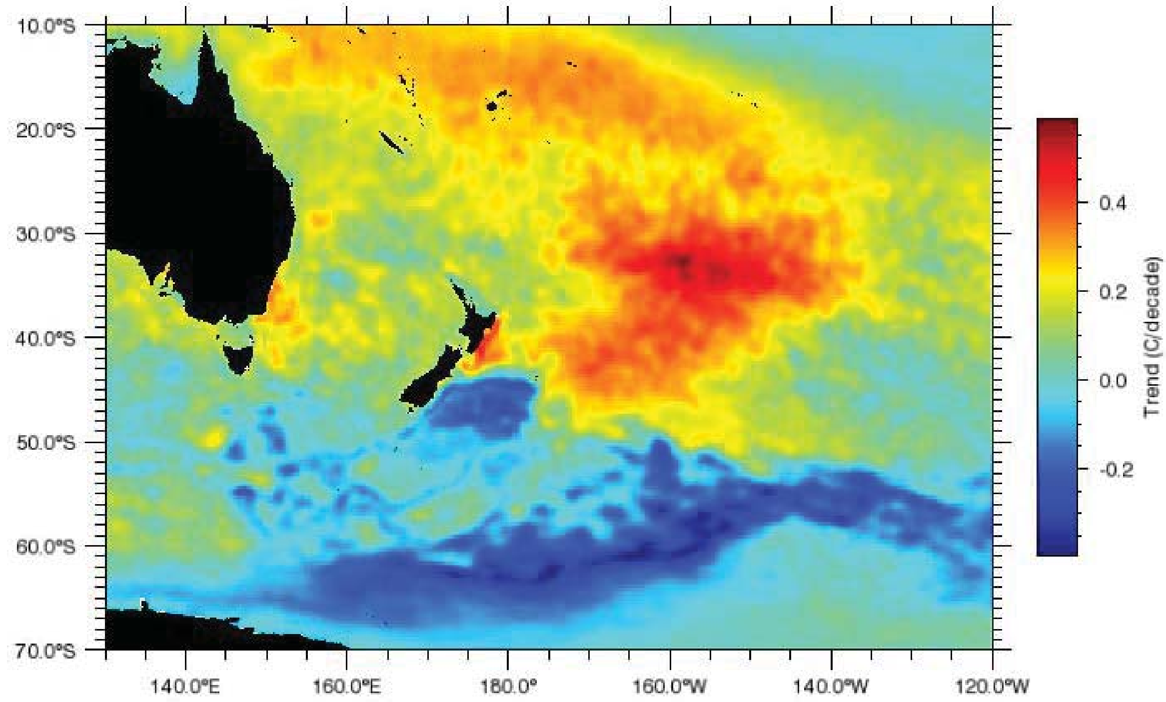

Figure 8.8: Trends in sea surface temperature, in °C/decade over the period 1982-2009. The data are again taken from NOAA, but are based on daily interpolated satellite measurements over a much finer 0.25° grid. See http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php. This product is the result of an objective analysis, an optimum interpolation rather than a pure satellite retrieval, so as to correct for issues like the effect of the Mt Pinatubo eruption aerosols on satellite detected radiances. It is described in Reynolds *et al.* (2007)

Sea surface temperatures (SST) derived from satellite data have been compared to empirical CTD measurements made from relevant sub-areas of the Chatham Rise and Sub-Antarctic during trawl surveys. This showed good correlations, reassuring us that satellite-derived SST provided a realistic measure of sea surface temperature for these regions in years before CTD data were available O'Driscoll *et al.* 2011).

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 negative relationship between SST and SOI is broadly consistent across the 40 years of data although the pattern is less clear post 1997 (Figure 8.9). The clearest fisheries example of a link between coastal SST and fish recruitment and growth is for northern stocks of snapper (*Pagras auratus*), where relatively high recruitment and faster growth rates have been correlated with warmer conditions from the Leigh SST series (Francis 1993, 1994a).

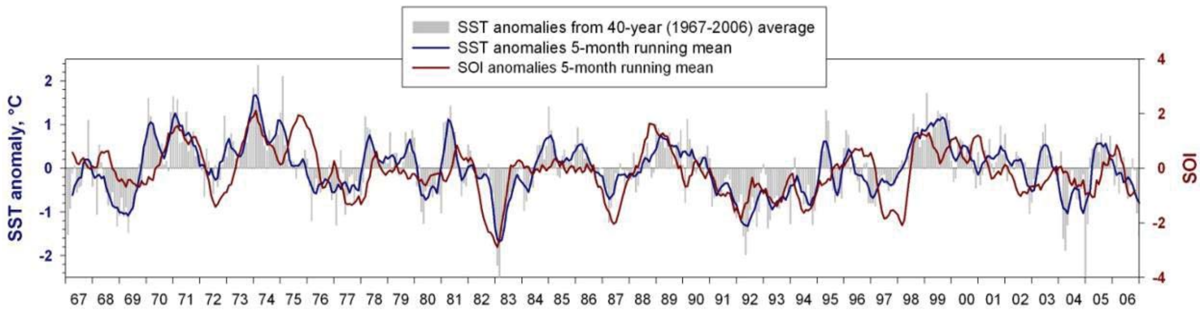

Figure 8.9: Sea surface temperature (SST) anomolies from SST measurements at Leigh (Auckland University Marine Laboratory) and Southern Oscillation Index (SOI) anomalies. (Image from Hurst et al 2012.)

Temperature fluctuations also occur at depth in the ocean as demonstrated by changes in temperature down to 800 m in the eastern Tasman Sea between 1992 and 2008 (Figure 8.10).

The ocean temperature between Sydney and Wellington has been sampled about four times per year since 1991. The measurements are made in collaboration with the Scripps Institution of Oceanography. Analyses of the subsurface temperature field using these data include Sutton & Roemmich (2001) and Sutton *et al.* (2005). The index presented for this transect (Figure 8.10) is for the most eastern section closest to New Zealand (161.5°E and 172°E). The eastern Tasman is chosen because it is closer to New Zealand, and because it has less oceanographic variability which can mask subtle interannual changes. The section of the transect shown is along fairly constant latitude is therefore unaffected by latitudinal temperature and seasonal cycle variation. The upper panel shows the temperature averaged along the transect between the surface and 800m and from 1991 to the most recent sampling.

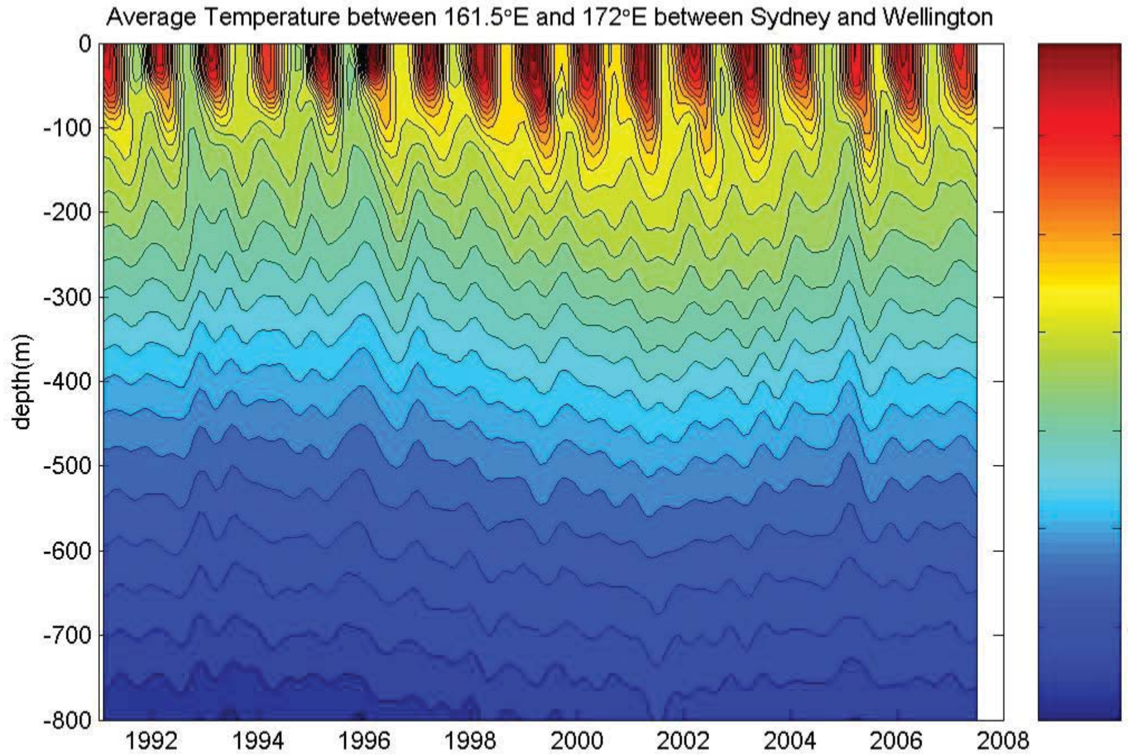

Figure 8.10: Eastern Tasman ocean temperature: Wellington to Sydney 1991–2008. Coloured scale to the right is temperature °C. (Image from Hurst *et al.* 2012, after Sutton *et al.* 2005)

The seasonal cycle is clearly visible in the upper 100–150m. 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 800m of the measurements (effectively the full depth of the eastern Tasman Sea). It also began during an El Niño, period when conditions would be expected to be cool. Finally, it was thought to be linked to a large-scale warming event centred on 40°S that had hemispheric and perhaps global implications. This warming has been 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 Ocean. Roemmich *et al.* (2007) hypothesized that the ultimate forcing was due to an increase in high latitude westerly winds effectively speeding up the entire South Pacific gyre.

Other phenomena have led to periods of warming that are not as yet fully understood. In particular a period of widespread warming in the Tasman Sea to depths of at least 800 m, 1996–2002 (Sutton *et* *al.* 2005). Both stochastic environmental variability and predictable cycles of change influence the productivity and distribution of marine biota in our region.

8.2.2. Climate variables

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 past 100 years, regime shifts occurred in 1925, 1947, 1977 and 2000 (Figure 8.11). The latest shift should result in New Zealand experiencing periods of reduced westerlies, with associated warmer air and sea temperatures and reduced upwelling on western coasts (Hurst *et al.* 2012).

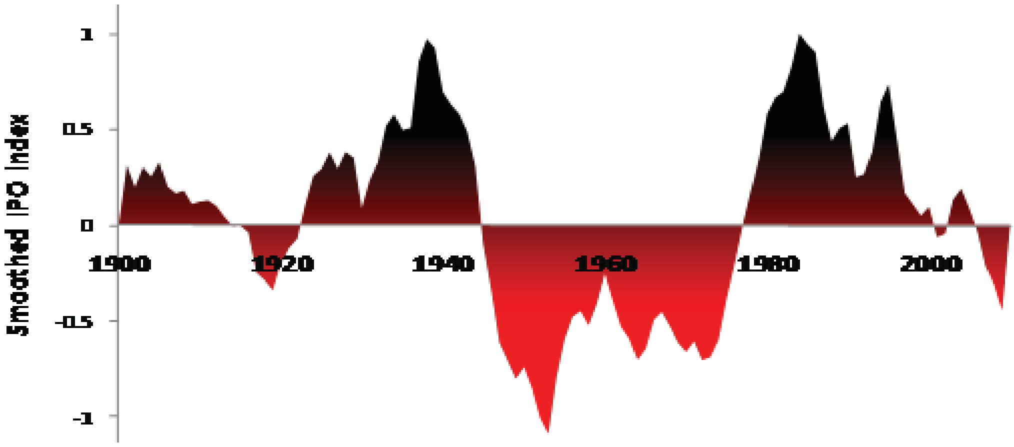

Figure 8.11: Smoothed index of the Interdecadal Pacific Oscillation (IPO) since 1900. (Image source NIWA based on data from the United Kingdom Meteorological Office, UKMO).

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). 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 (Hurst *et al.* 2012). When the SOI is strongly negative, an El Niño event is taking place and New Zealand tends to experience increased westerly and south-westerly winds and cooler, less settled weather and enhanced along shelf upwelling off the west coast South Island and north east North Island (Shirtcliffe 1990, Zeldis *et al.* 2004, Chang & Mullan 2003). The SOI is available monthly from 1876 (Mullan 1995) (Figure 8.12).

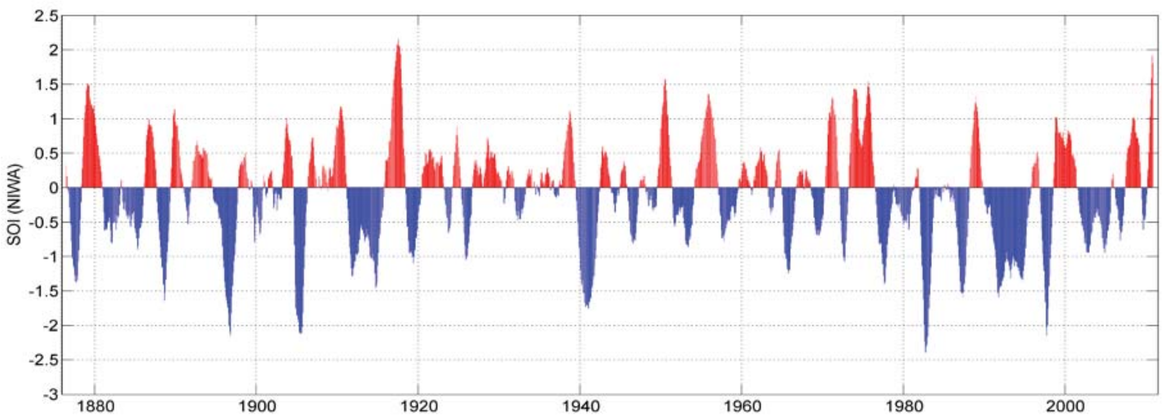

Figure 8.12: Southern Oscillation Index (SOI) 13-month running mean 1876-2010. Red indicates warmer temperatures, blue indicates cooler conditions for New Zealand. (Image courtesy of NIWA.)

8.2.3. Ocean acidification

An increase in atmospheric CO_2 since the industrial revolution has been paralleled by an increase in CO_2 concentrations in the upper ocean (Sabine *et al.* 2004), with global ocean uptake on the order of ~2 gigatonnes (Gt) per annum (~30% of global anthropogenic emissions, IPCC, 2001a). The anthropogenic CO_2 signal is apparent to an average depth of ~1000m.

The increasing rate of CO_2 input from the atmosphere has surpassed the ocean's natural buffering capacity and so the surface of the ocean ocean is becoming more acidic. This is because carbon dioxide absorbed by seawater reacts with H_2O to form carbonic acid, the dissociation of which releases hydrogen ions, so raising the acidity and lowering pH of seawater. Since1850, average surface 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 150% increase in hydrogen ion concentration. Both the predicted pH in 2100 and the rate of change in pH are outside the range experienced by the oceans for at least half a million years. In the absence of any decrease in CO_2 emissions this trend is proposed by Caldeira & Wickett, (2003) to continue.

In New Zealand, the projected change in surface water pH between 1990 and 2070 is a decrease of 0.15-0.18 pH units (Hobday *et al.* 2006). The only time series of dissolved pCO2 and pH in NZ waters is the bimonthly sampling of a transect across neritic, subtropical and subantarctic waters off the Otago shelf since 1998 (University of Otago/NIWA Munida Otago Shelf Time Series). Dissolved pCO_2shows some indication of an increase although this is not linear and does not correlate with rise in atmospheric CO_2 (see Fig 8.13).

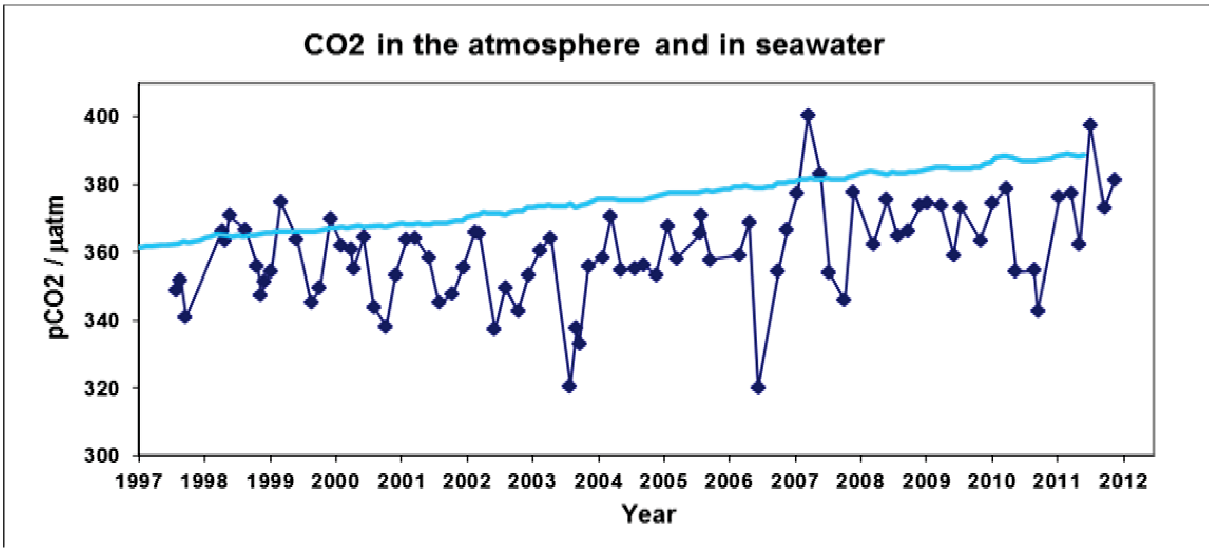

Figure 8.13: pCO_2 (partial pressure of CO_2) in subantarctic surface seawater from the *R.V. Munida* transect, 1998–2012. (Image courtesy of K. Currie, NIWA)

The Munida time-series pH data shows a decline in subantarctic surface waters since 1998 (Fig 8.14). Addition of a sine-wave function to the pH data suggests a) a linear decline in surface water pH and b) that winter time pH values are consistent with that expected from equilibrium with atmospheric CO_2 as recorded at the NIWA Baring Head atmospheric station (K. Hunter (U. Otago) & K. Currie (NIWA), pers comm.). The oscillations are primarily due to seasonal changes in water temperature and biological removal of dissolved carbon in the seawater. The time series sampling period is currently too short to distinguish long-term changes from seasonal and interannual variability, and it is not yet possible to attribute observed changes to uptake of anthropogenic carbon dioxide.

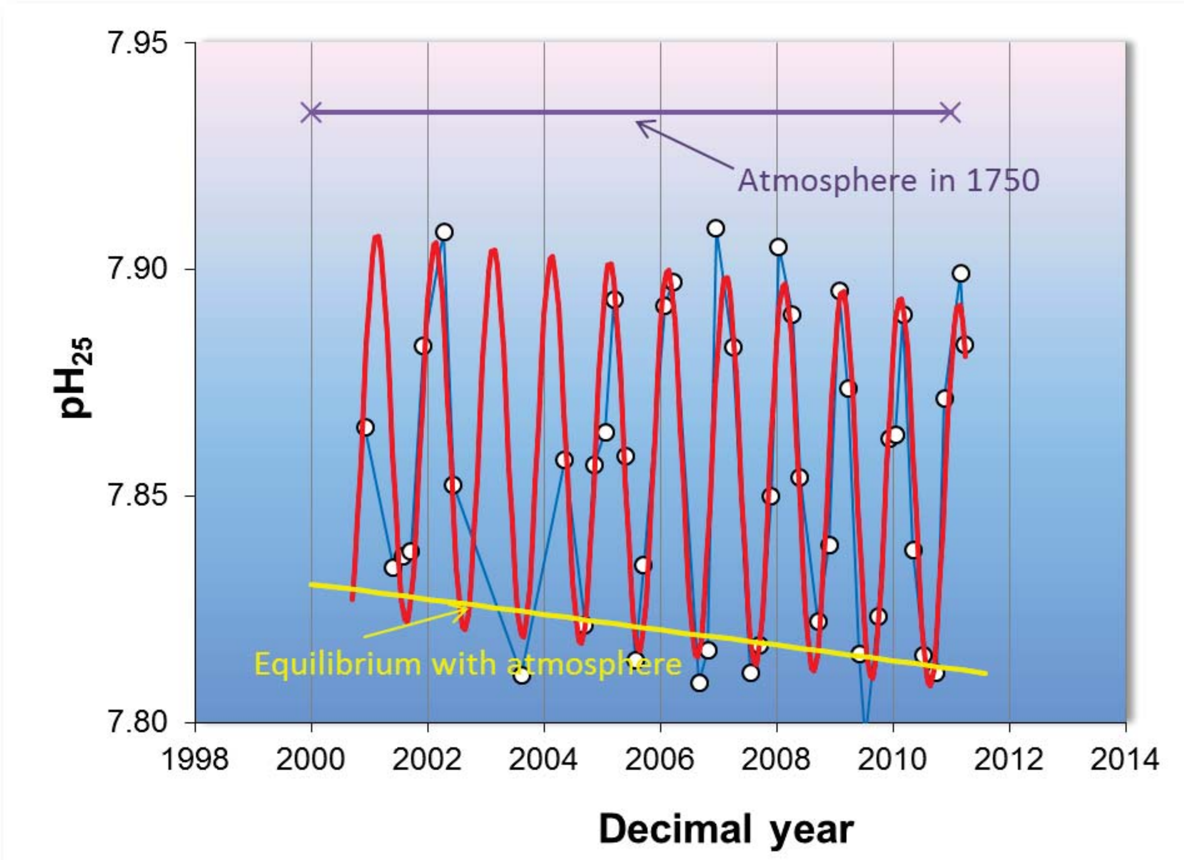

Figure 8.14: pH in Sub- Antarctic surface seawater on the *R.V. Munida* transect, 1998–2006. The blue points and joining lines are the actual measurements, and the red line a best fit to the points using a sine wave function (to represent seasonal change). The black line represents what pH assuming equilibrium with the atmosphere concentration in the Year 1750. The yellow line is the pH assuming equilibrium with actual CO2 concentrations measured at the NIWA Baring Head Atmospheric Station. pH^{25} is the pH measured at 25°C (Image Source: A Southern Hemisphere Time Series for CO2 Chemistry and pH K. Hunter, K.C. Currie, M.R. Reid, H. Doyle. A presentation made at the International Union of Geodesy and Geophysics (IUGG) General Assembly Meeting, Melbourne June 2011.)

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, biological activity in the seawater and sediment and other coastal processes. Surface pH in the open ocean has been determined on a monthly basis at the BATS (Bermuda Time Series Station) in the North Atlantic since 1983 (Bates 2001, 2007), and at HOT (Hawaiit Time Series Station) in the North Pacific since 1988 (Brix *et al*. 2004, Dore *et al*. 2009). Both time series records show long term trends of increasing pCO_2 (partial pressure of CO_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 (Figure 8.15). Placed in the context of these longer time series of atmospheric CO_2 measurements, the short record of the Munida SubAntarctic Water time series shows pCO_2 and pH in surface seawater tracking the atmospheric CO_2 (Figure 8.14). In addition, the regional means of seawater pH differ significantly with temperature, with the South Pacific at the lower end (Feely *et al* 2009).

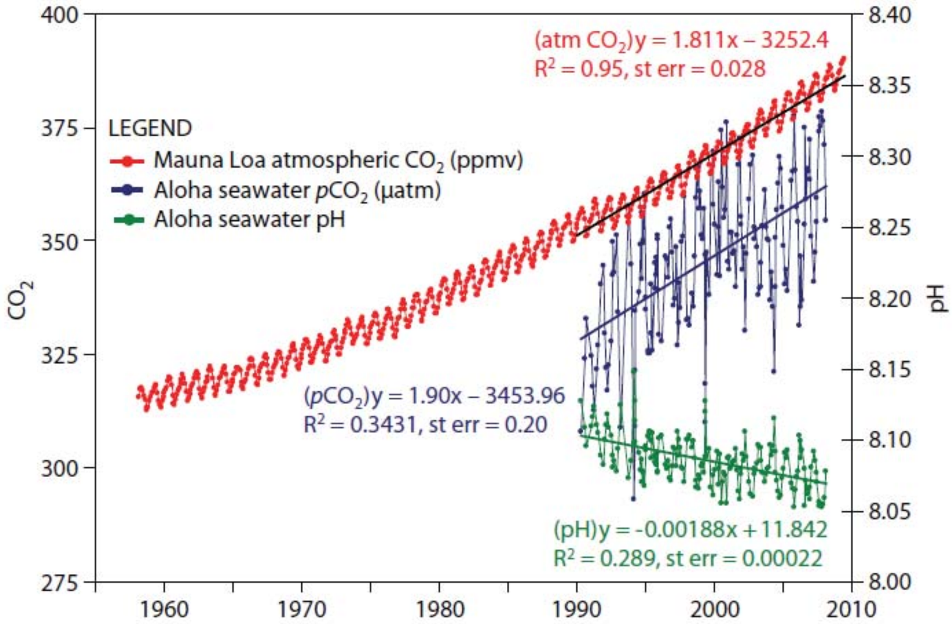

Figure 8.15: Time series of atmospheric carbon dioxide at Moana Loa, seawater carbon dioxide and surface ocean pH at Ocean station ALOHA in the subtropical North Pacific Ocean near Hawaii. pH is shown as *in situ* pH, based on direct measurements and calculated from dissolved inorganic carbon and alkalinity in the surface layer (after Dore *et al.* 2009). (Image directly sourced from Feely *et al.* 2009 with permission.)

Biological implications of ocean acidification result from increasing dissolved pCO_2, increasing hydrogen ions (decreasing pH) and decreasing carbonate availability. The concern about ocean acidification is that the resulting reduction in carbonate availability may potentially impact organisms that produce shells or body structures of calcium carbonate, resulting in a redistribution of an organism's metabolic activity and increased physiological stress. Organisms most likely to be affected are those at the base of the food chain (bacteria, protozoa, plankton), coralline algae, rhodoliths, shallow and deepwater corals, echinoderms, molluscs, and possibly cephalopods (e.g., squids) and high-activity pelagic fish (e.g., tunas) (see Feely *et al.* 2004 and references therein; Orr *et al.* 2005, Langer *et al.* 2007). This is particularly of concern for deep-sea habitats such as seamounts, which can support structural reef-like habitat composed of stony corals (Tracey *et al.* 2011) as well as commercial fisheries for species such as orange roughy (Clark 1999). A shoaling carbonate saturation horizon could push such biogenic structures to the tops of seamounts, or cause widespread die-back (e.g., Thresher *et al.* 2012). This has important implications for the structure and function of benthic communities, and perhaps also for the deep-sea ecosystems that support New Zealand's key deepwater fisheries. Conversely some groups, including phytoplankton and sea-grass, may benefit from the increase in dissolved pCO_2 due to increased photosynthesis.

Direct effects of acidification on the physiology and development of fish have also been investigated. This has particularly focussed on the freshwater stages of salmonids (due to the widespread occurrence of pollution-derived acid rain) but increasingly in marine fish, where adverse effects on physiology development have been documented (e.g. Franke, and Clemmesen, 2011). Such studies highlight the potential for increasing acidification to impact larval growth and development, with implications for survival and recruitment of both forage fish and fish harvested commercially.