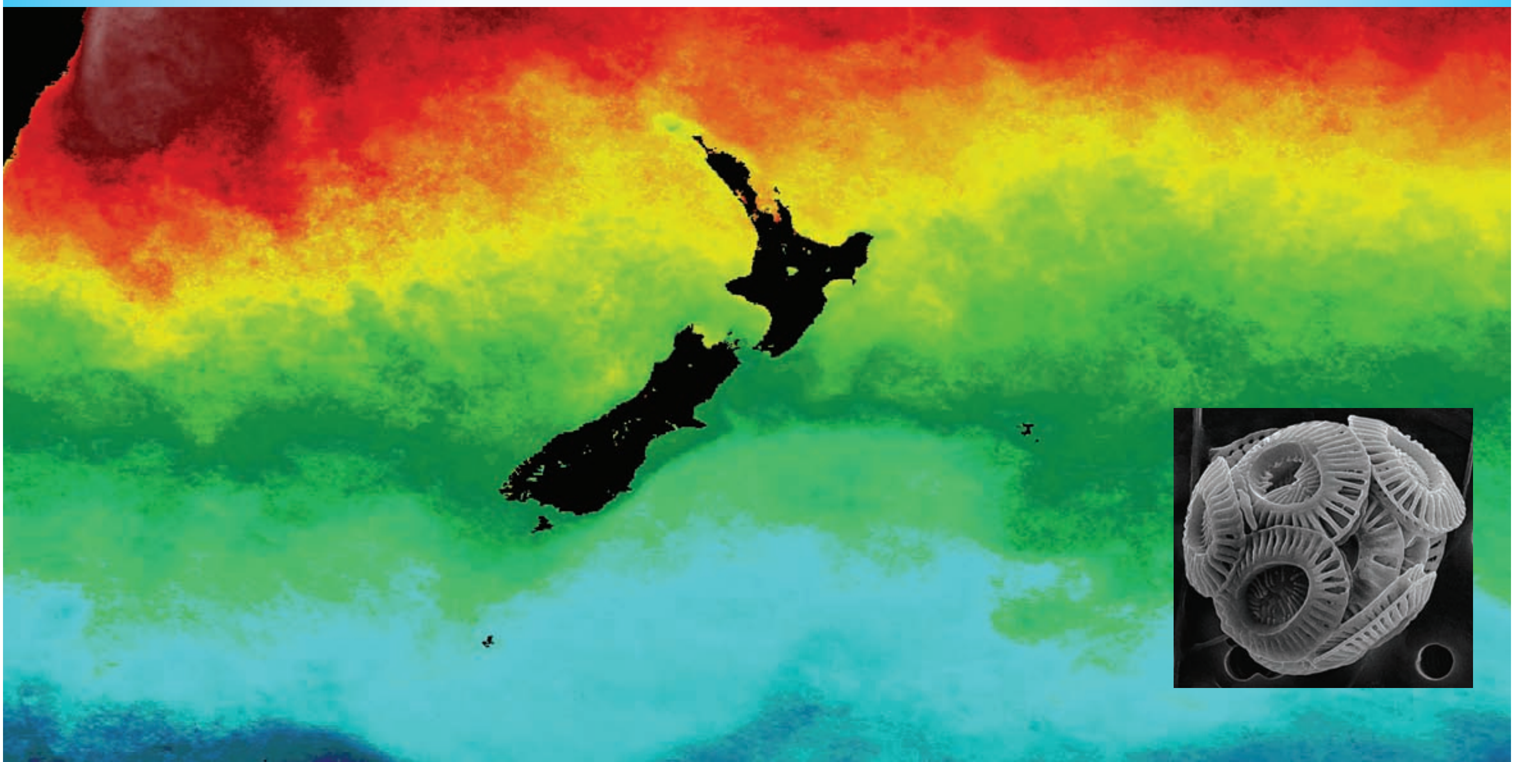
NIWA
Taihoro Nukurangi

An Ocean Climate Change Atlas for New Zealand waters

A primer for a major new web-based tool to help predict how oceanic species will be affected by climate change



Philip W. Boyd & Cliff S. Law

NIWA Information Series No. 79
2011
ISSN 1174-264X

Foreword

Climate change will affect the New Zealand landmass, with major implications predicted for agriculture and other land use patterns. At the same time, the seas surrounding New Zealand will be modified by a changing climate – with up to a 4 ºC warming predicted by some models in the coming century in some places. We need to understand the implications of climate change on our ocean, and how our marine economy and cultural heritage will in turn be altered.

New Zealand's Exclusive Economic Zone (EEZ) is one of the largest globally (15 times the land surface area). It is a complex tract of ocean comprising different water bodies each with their own distinctive plants, animals, and ocean environmental characteristics. The value of the resources harvested within the EEZ is estimated to be over NZ$4 billion per annum.

Climate change will modify environmental characteristics in the EEZ. This will impact on its productivity and diversity, with implications for the future management and conservation of stocks, and the economic value of EEZ resources.

NIWA is developing a web-based Ocean Climate Change Atlas, due to be released in 2012. The atlas will map where key groups reside, reveal how each water body will be altered in the coming decades, and report on the vulnerability to environmental change of the key species within the EEZ.

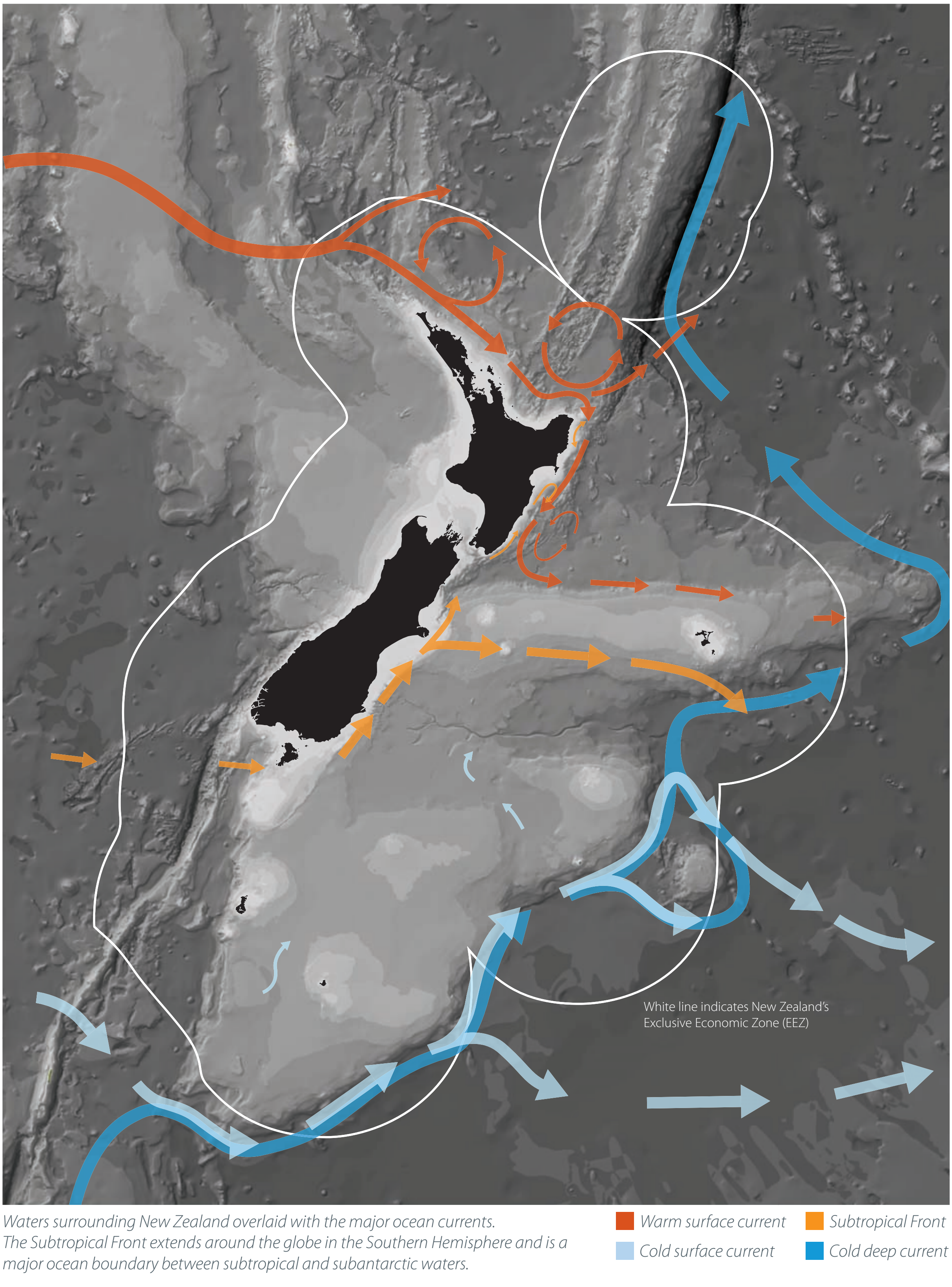
This short publication provides illustrative examples from the atlas, showing how marine biota may respond to future change.

Forewarned is forearmed; understanding what is happening in our seas is an essential step in dealing with these approaching issues, by facilitating forward planning for the sustainable management and effective stewardship of the EEZ.

Dr. Charlotte Severne
Chief Scientist for Oceans
July 2011

Contents

Ocean properties and their influence on plant and animal life



Waters surrounding New Zealand overlaid with the major ocean currents. The Subtropical Front extends around the globe in the Southern Hemisphere and is a major ocean boundary between subtropical and subantarctic waters.

The ocean is not uniform. Instead, it is made up of ocean currents and separate water bodies, each of which differs substantially in characteristics such as temperature or plant nutrient stocks. Regional variations in these properties determine which organisms reside where.

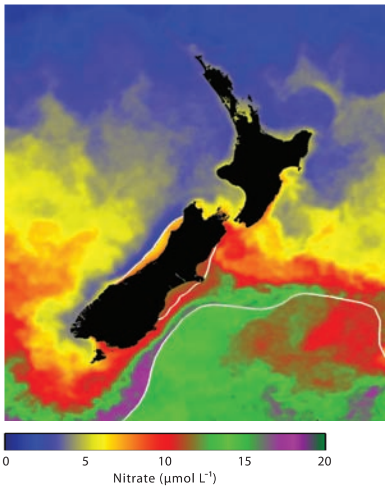
All marine organisms have fixed temperature ranges, like their counterparts on land, and so the distribution of different species is primarily related to water temperature.

Sunlight too is an important factor. It drives photosynthesis by phytoplankton, which provides the energy source at the base of the food chain. Sunlight can penetrate up to 100 metres into the upper ocean, depending on the clarity of the water, which varies regionally.

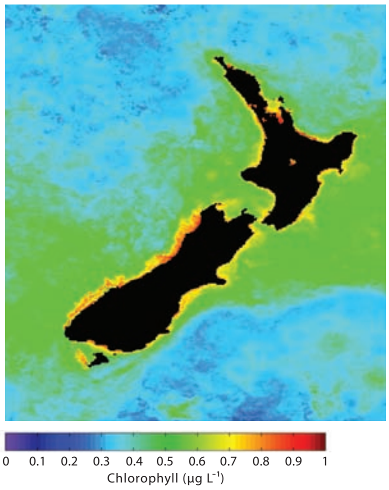
The amount of plant nutrients varies widely in New Zealand's surface waters, with a north to south increase in nutrient stocks. Nutrient availability determines the productivity of each region, which in turn sets the amount of energy available to the foodweb in each water body.

High carbon dioxide in surface waters lowers both the pH (called ocean acidification) and carbonate availability. Carbonate is needed by plankton, corals, and molluscs to produce shells.

The New Zealand EEZ is characterised by a pronounced north-to-south decrease in upper ocean temperatures as evident from this satellite image, with warmer subtropical waters in the north being separated from cooler subantarctic waters to the south by an oceanic front – the Subtropical Front.



An EEZ-wide plot of the concentration of the plant nutrient nitrate, which ranges from very low concentrations in warmer subtropical waters to high concentrations in cooler subantarctic waters. This map was obtained from satellite images of temperature and chlorophyll, with nitrate values estimated from predicted relationships between each ocean property.



A satellite image of chlorophyll concentrations reveals a wide range of phytoplankton stocks, from low stocks in subtropical waters north of New Zealand to much higher stocks to the east and west of New Zealand. Waters to the south-east of New Zealand have plenty of plant nutrients, but phytoplankton cannot use these as they lack sufficient iron.

Subtropical to subantarctic – how plant and animal life varies across the EEZ

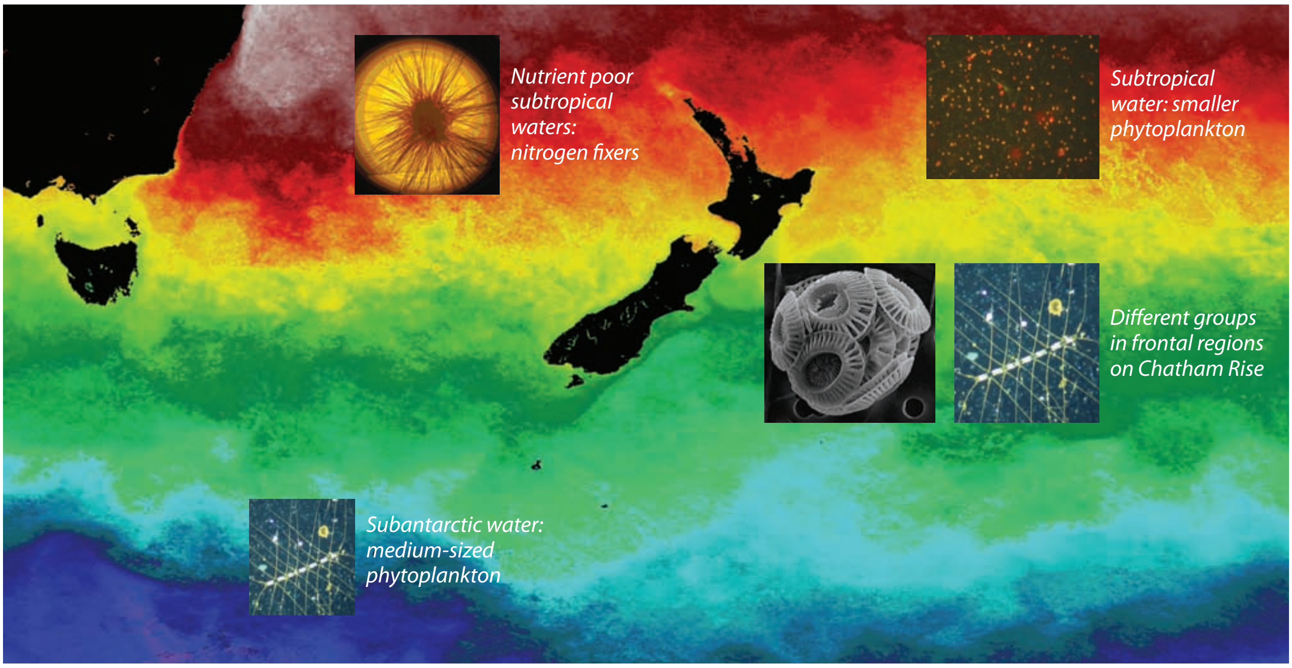
In the EEZ, different water bodies are conspicuous, ranging from subpolar waters in the south to subtropical waters in the north. Consequently, water properties vary regionally.

Subtropical waters in the northern EEZ have very low nutrient levels. The resident phytoplankton are small and their growth is restricted by the amount of the plant nutrient nitrate, with some phytoplankton fixing nitrogen gas to meet their daily nutrient requirements.

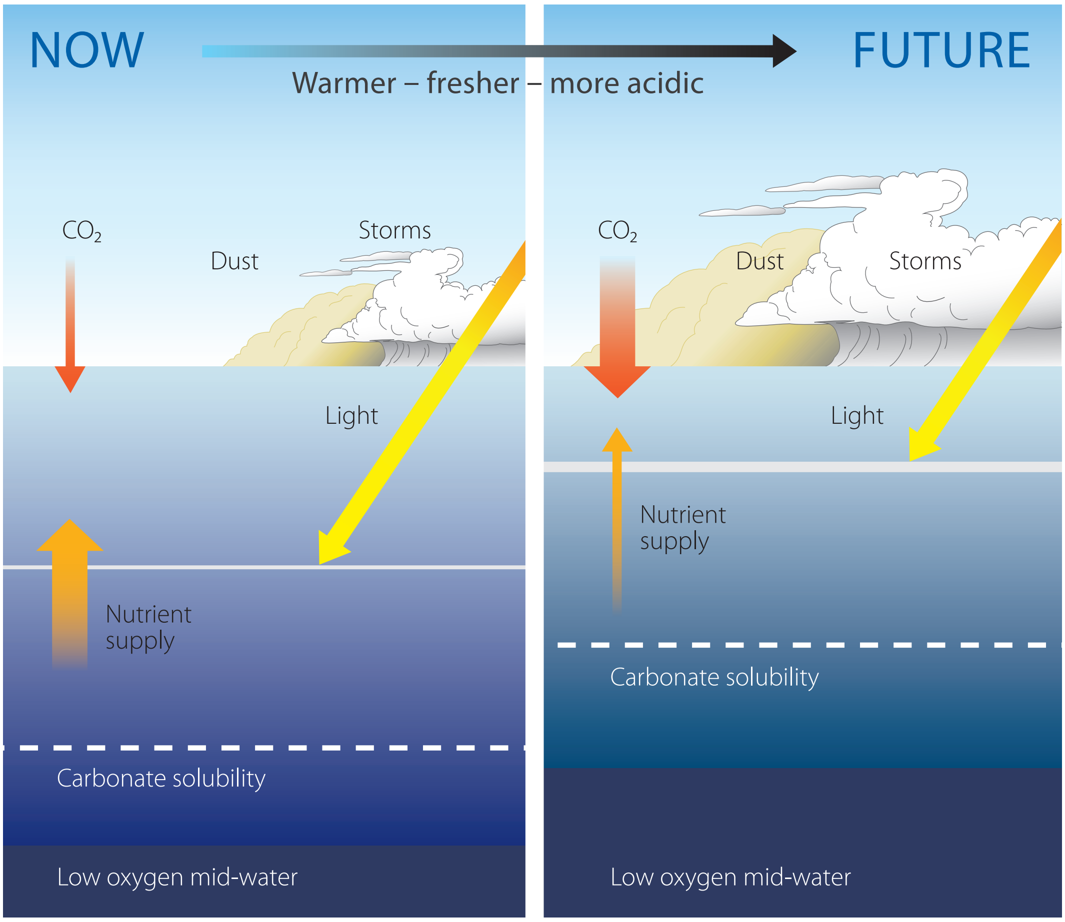
In contrast, subantarctic waters in the southern EEZ have higher nutrient levels and support phytoplankton species which are larger. However, these waters are not the most productive in the EEZ, as plankton growth is restricted by lack of the trace element Iron.

The most productive areas tend to be where different water masses meet, for example, at the Subtropical Front over the Chatham Rise to the east of New Zealand.

The different environmental characteristics of each water body are reflected in different resident plants and animals (biota).



Satellite image of surface ocean temperature overlaid with images from microscope photography of the main phytoplankton species in subtropical, and subantarctic waters.



A summary of the many changes that are anticipated in ocean properties from surface waters to the deep ocean in the coming decades due to a changing climate.

How will climate change alter ocean properties?

Climate change will alter many ocean properties and manifest itself in different ways across the EEZ.

As with climate change studies on land or in the atmosphere, sophisticated global climate models provide projections for the coming decades for the ocean. A range of computer models predict that around New Zealand:

- surface waters will warm, freshen (i.e., become less salty), and so become less dense. This will increase the density gradient between surface and deeper waters (i.e., stratification), which will reduce the upward supply of plant nutrients to the surface from deeper waters
- the surface layer where the phytoplankton live will become shallower and so the phytoplankton will receive more light
- the warmer ocean will contain less dissolved oxygen, and the volume of the mid-water column oxygen-deficient zones will increase
- increasing carbon dioxide in the atmosphere will enter the ocean making it more acidic and causing carbonate shells to dissolve at shallower depths
- there will be large-scale changes in wind fields, affecting ocean currents and vertical mixing
- storm frequency and dust deposition will increase, influencing nutrient supply.

The Southern Ocean's properties are already changing

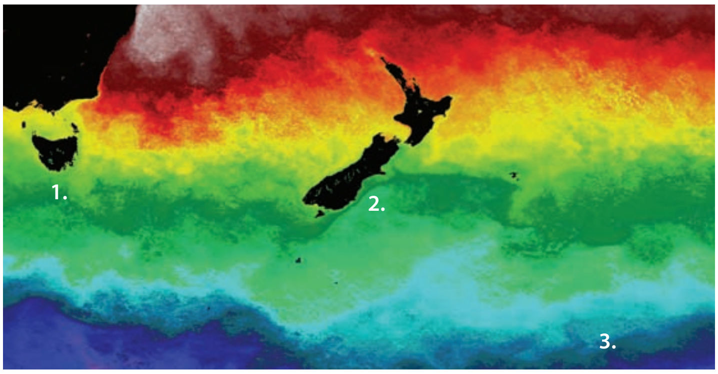
Although we rely heavily on computer model simulations to predict the effects of climate change on the ocean, measurable changes in ocean properties are already evident in our seas.

Atmosphere warming and changes in ocean currents have already caused the surface temperature of the Tasman Sea near Australia to increase, at four times the rate observed for the rest of the global ocean over the same period.

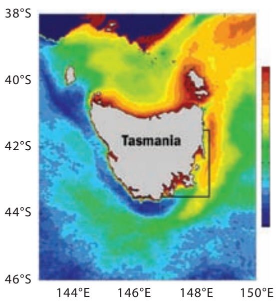
Closer to home, ten years of monthly monitoring has shown a decline in the pH of subantarctic waters off Otago that is probably due to the recorded increase in atmospheric carbon dioxide and subsequent uptake by the ocean. This trend is consistent with that observed in long-term time-series studies in other regions of the ocean.

A suite of observations at land-based sites (including Baring Head near Wellington) around the Southern Ocean reveal that this large body of water is soaking up less atmospheric carbon dioxide than predicted by computer models. This recent departure between observations and model simulations is thought to be due to increased wind strength around the Southern Ocean, which stirs up the ocean making it less efficient at storing carbon dioxide from the atmosphere.

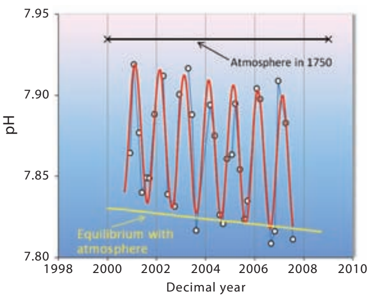
As the ocean has soaked up over 40 percent of the atmospheric carbon dioxide released since the Industrial Revolution, a reduction in the storage capacity of the Southern Ocean may accelerate the build-up of carbon dioxide in the atmosphere.



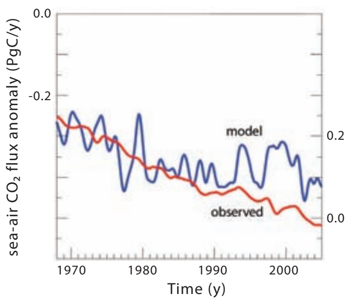
Satellite image of sea surface temperature around New Zealand, with the locations indicated of the climate changes studies below.



1. *Warming of the ocean near Tasmania by up to 1 °C over 1992–2006.*



2. *Observed decrease in pH in the waters off Otago between years 2000 and 2008.*



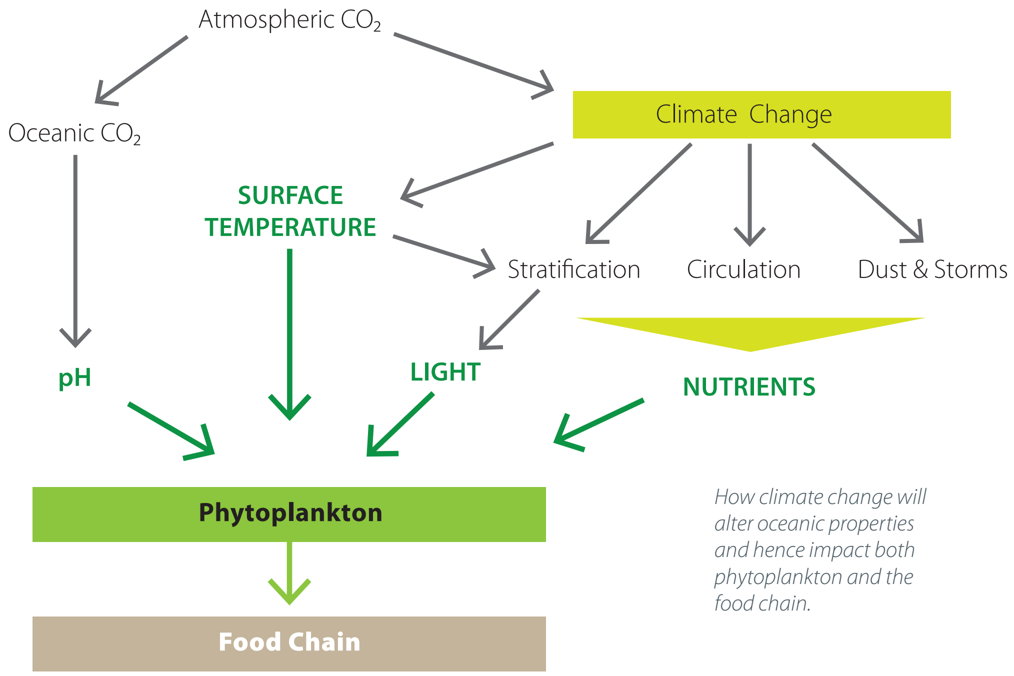
3. *Less efficient uptake of atmospheric CO_2 by Southern Ocean waters due to windier conditions.*

How the base of the food chain will be altered

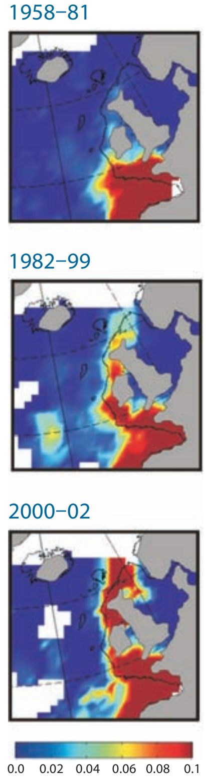
Phytoplankton are the base of the oceanic food chain, and their stocks, productivity, size, and diversity determine the amount of carbon and energy available, and so which groups and species are supported further up the food chain. The makeup of the phytoplankton community is stable under constant conditions, but when oceanic systems are altered, unpredictable swings in phytoplankton diversity and abundance can occur. In extreme cases invasive species, such as harmful and/or toxic algae, may thrive.

Higher in the food chain, altered ocean properties, such as ocean warming, can also directly impact grazers such as zooplankton that feed upon the phytoplankton. For example, in the North Atlantic, warm-water zooplankton communities have extended their distribution northwards by more than ten degrees of latitude since the 1960s.

Change in underwater light levels and warming may influence food webs by altering the length of the growing season and hence the timing of events such as the spring bloom of phytoplankton. Many grazers, in particular their larval or juvenile stages, rely upon such productive events to bolster their growth rates at a stage in their development when they are particularly vulnerable.



How climate change will alter oceanic properties and hence impact both phytoplankton and the food chain.



The average number of warm water zooplankton species (red), showing an increase in the northern Atlantic Ocean since 1958.

Environmental impacts

The plants and animals that occupy higher trophic levels, including those that support fisheries, will be affected by both direct and indirect effects of climate change.

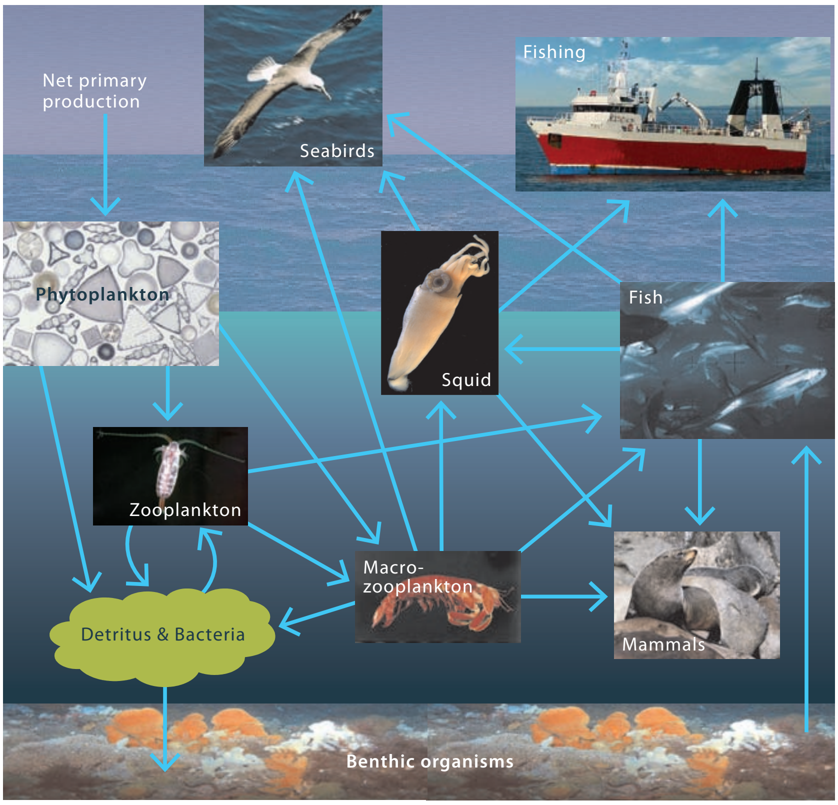
Direct physiological impacts of a warmer ocean on higher trophic levels include changes in metabolism and reallocation of energy and other resources that influence growth, reproduction, and recruitment. Less available oxygen will also influence the growth and distribution of the biota that occupy higher trophic levels.

Ocean acidification has been shown to affect reproduction, behaviour, and physiological functions of some species.

The impact of such direct effects of climate change may strike particularly hard at certain stages of the life cycle of an organism. For example, an adult organism may be unaffected by a change in temperature or pH, whereas its eggs or larvae may be unable to fully develop.

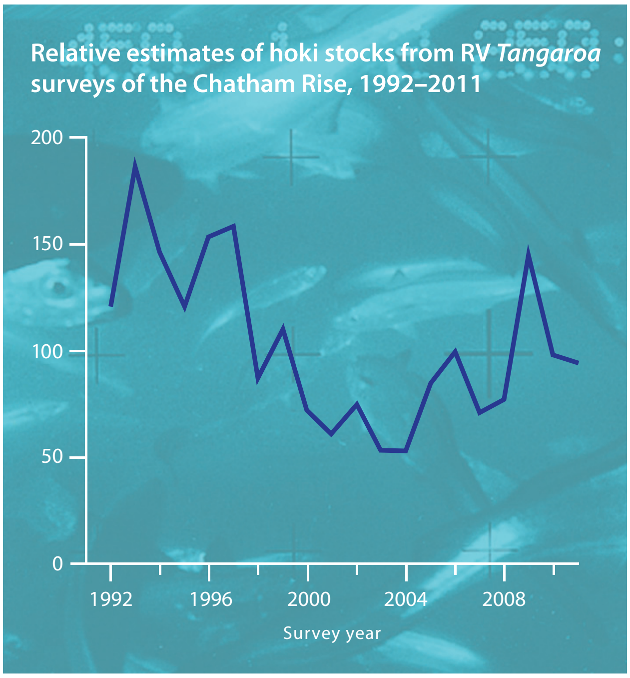
Indirect effects of climate change for animals could include geographic shifts in the distributions of prey, such as plankton. This may lead to a rapid and perhaps irreversible change in species composition, such as a shift in the dominant fish species.

As changes to ocean ecosystems begin to happen, New Zealand's fisheries could well be affected.



A schematic of the relationships between predators and prey for the Campbell Plateau, southeast of the South Island. Arrows show the flows of energy between the bottom of the foodweb and higher trophic levels.

Putting it together – environmental and economic impacts



Economic impacts

The marine resources across our EEZ support a thriving economy. In 2010, wild fisheries catch and export was valued at over NZ$4 billion dollars per annum, and supported over 10 000 jobs. Cultivated fisheries, including aquaculture and shellfish, added almost a further NZ$0.5 billion dollars annually.

The open ocean also provides a wide range of so-called 'ecosystem services' that we are only just beginning to evaluate. For example, they supply nutrients to onshore waters that drive and sustain inshore fisheries, such as the scallop fisheries in Tasman and Golden Bays. Locally, the open ocean also plays a significant role in sustaining biota that are valuable tourist assets such as whale-watching.

At a regional and global level, the oceans have absorbed and now store around 40% of the carbon dioxide released by fossil fuel burning. These services are more difficult to put a price on but are essential to sustaining the current economy of New Zealand.

The loss of even a small proportion of such resources and the revenue associated with them, due to a changing climate, could have a pronounced economic impact.

Who lives where in the EEZ – from microscopic plants to fish

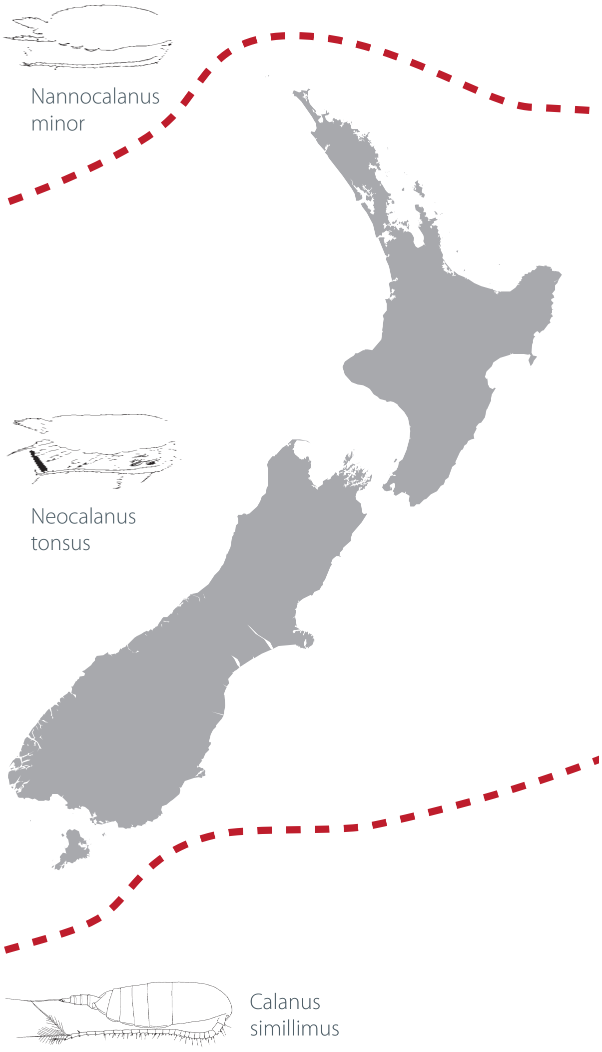
The distribution of marine life across the New Zealand EEZ is determined using a wide range of tools and approaches. These range from satellite data that provide high-resolution distribution maps of surface properties to ship-based surveys – for example of phytoplankton activity across different water bodies. Satellites pass over New Zealand each day and provide images of surface phytoplankton stocks that, over time, reveal clear distributional trends. Massive blooms of some phytoplankton groups, such as coccolithophores, are readily apparent from space. This combination of satellite maps and ship survey maps provides reliable information on what phytoplankton groups reside where. These maps, along with data on ocean properties in each water body, provide clues as to which ocean properties define the distributions and boundaries of each phytoplankton group.

Mapping the distribution of marine life higher in the food chain is generally more time-consuming than mapping phytoplankton. Underwater camera and trawl surveys, from research ships, require many years of surveys to build up the distribution maps used here.

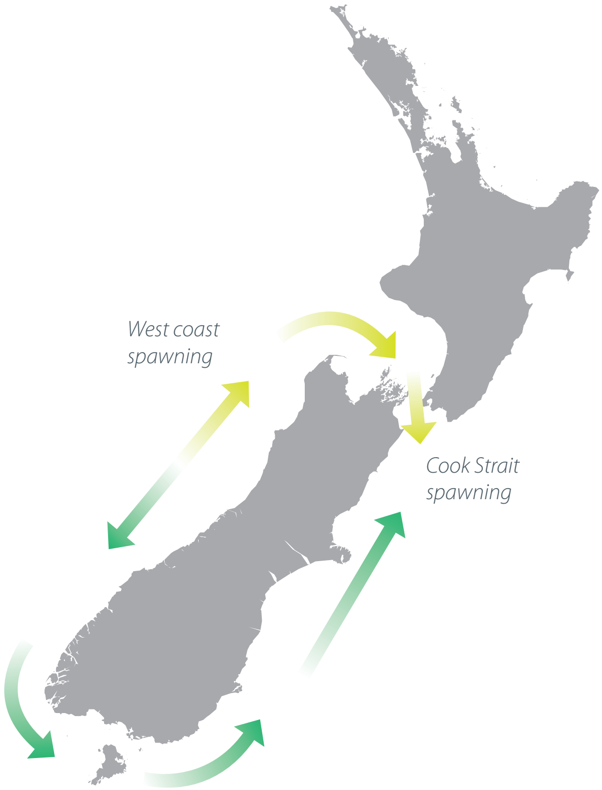
A range of factors determines what lives where. For example:

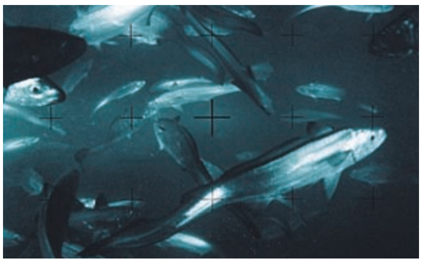
- **temperature:** some species, such as some corals or zooplankton, can only survive within a very narrow temperature range
- **interaction of environmental factors:** for example, current speed and pH
- **substrate type:** influences the settlement of some bottom dwellers such as deep-water corals.
- **life-cycle factors:** for example, hoki travel to distinct regions for spawning; in addition, juveniles also have different distribution patterns to adult hoki.

Sampling fish on board RV Tangaroa *to conduct a trawl survey of stocks.*



The New Zealand EEZ is characterised by a range of animal plankton (zooplankton, see image below) many of which have distinctive geographical locations. For example, Calanus simillimus *is found only in cooler subantarctic waters,* Nannocalanus minor *is found in tropical to warm subtropical waters whereas* Neocalanus tonsus *ranges from subantarctic to well north of the Subtropical Front.*





Organisms that are higher in the foodweb, such as fish, often exhibit complex distributional patterns. For example, hoki tend to spawn off the west coast of the South Island and then as they grow older (12 months) will move into different water masses to feed. The green and yellow arrows in the figure show two distinct pathways of movement used by young hoki.

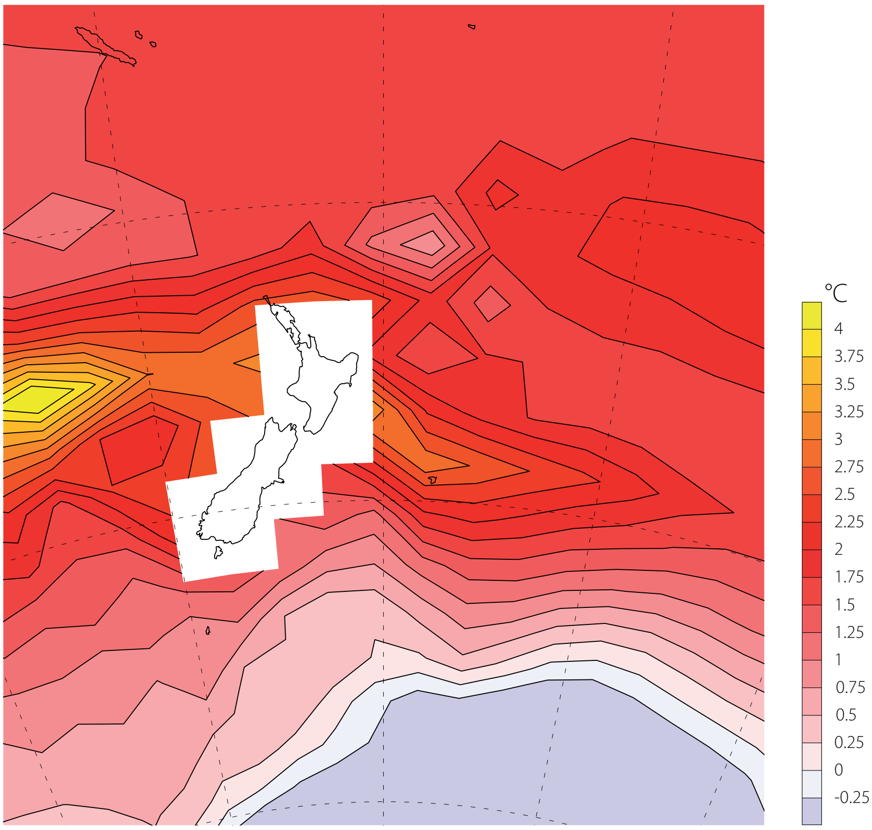
How will environmental properties in the EEZ be altered by a changing climate?

Although there is already published evidence of the dramatic alteration of ocean properties, such as the rapid warming of the surface waters at a site in the S.W. Tasman Sea, the most powerful tools to assess how the ocean will be altered by climate change are mathematical models that incorporate atmospheric, terrestrial, and oceanic data. Such models are the accepted standard approach to future prediction, and are run on powerful supercomputers to provide simulations of the future modification of New Zealand's EEZ waters resulting from climate change.

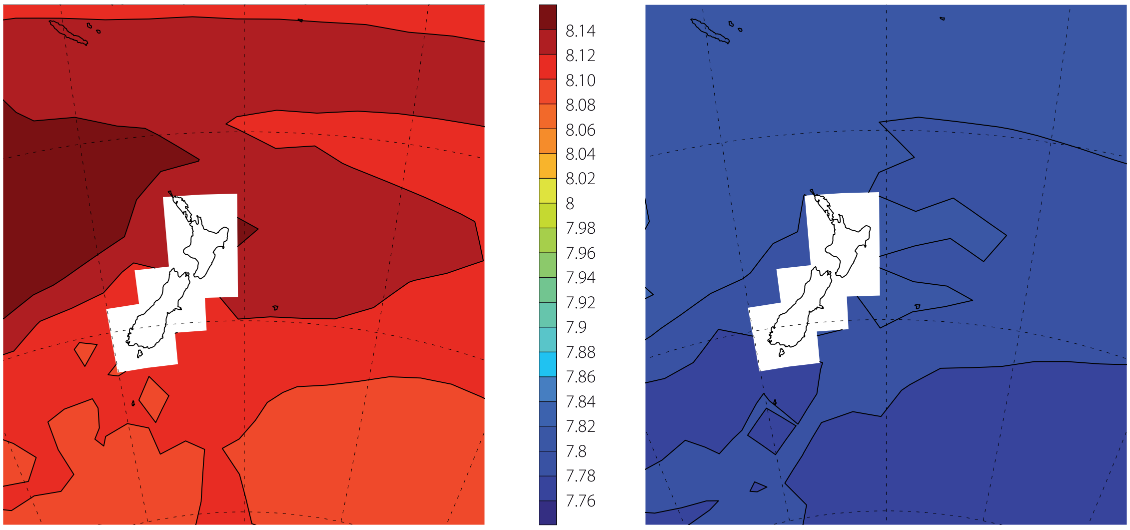
The models rely upon rigorous checks and balances for the quality assurance needed to back up these projections. For example, datasets comprising 50 years of ocean observations (from 1960 to 2010) are used to test the model performance.

The diagram below shows an example of a projection made with a particular climate model, for sea surface temperature changes towards the end of this century, under a scenario where the "carbon dioxide equivalent" concentration in the atmosphere in 2100 is about 3.3 times current levels. These projections demonstrate that warming in the coming century will not be uniform across the EEZ, nor will it reflect a simple north-to-south gradient. Instead, distinct surface warming trends are apparent across the EEZ, with this model predicting a 4 ºC warming by the end of the century for the Tasman Front west of New Zealand, intermediate warming on the Chatham Rise, and little change in ocean surface temperatures in subantarctic waters.

Predicted warming will also extend to deeper waters – with this modeled scenario predicting up to 2.5 ºC warming at 400 m and 1 ºC at 800 m depth.



Surface temperature difference between 1990-99 and 2090-99 for the scenario described in the text.



Surface pH for the decade 1990 to 1999.

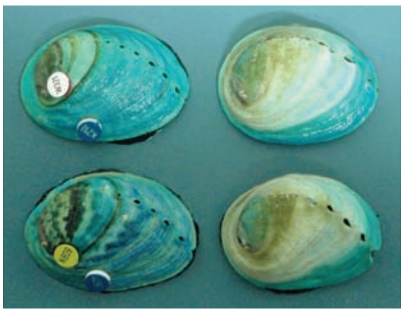
Surface pH projected for the decade 2090 to 2099, for the scenario described in the text.

In addition to warming, the environmental properties of EEZ waters will be altered in many other ways (e.g. fresher, more acidic, reduced supply of plant nutrients from deep waters). Offshore waters, including our EEZ, are predicted to become more acidic as the ocean continues to absorb carbon dioxide emissions and pH decreases.

The predicted acidification from this model (see above diagrams) appears small at first glance as pH is expressed on a logarithmic scale, which tends to minimise the spatial differences in altered pH (0.3 to 0.35 decrease in pH). The predicted pH decrease over the next century of up to 0.35 units does not look particularly significant, but this rate of acidification is without precedent over the last 25 million years. Once again the region which may be most altered is the upper ocean west of New Zealand in the Tasman Sea.

pH is also predicted to decrease in the subsurface waters of our EEZ, although to a lesser extent than in surface waters, with implications for mid-water and benthic biota.

Acidification will have many impacts on our EEZ. It may result in more rapid dissolving of certain organisms with carbonate shells, such as some species of oysters, mussels, and carbonate-containing plankton. In addition, it will make the formation of such carbonate skeletons more difficult for some species.



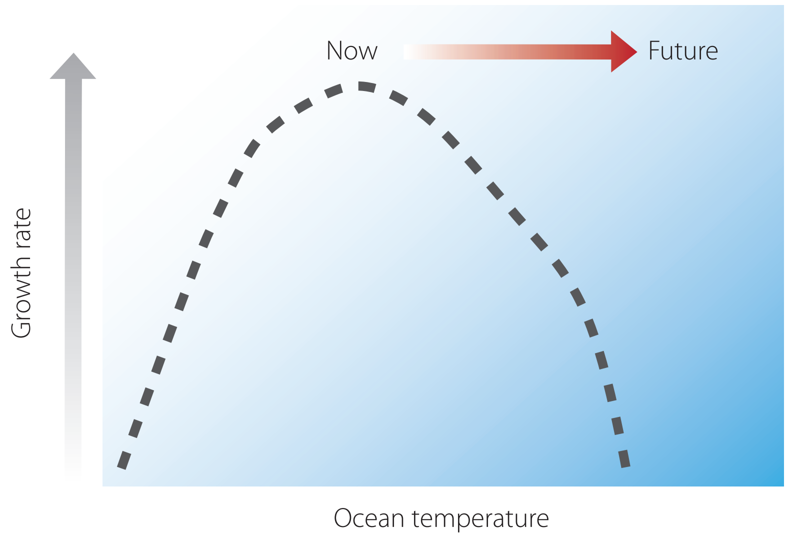
Examples of paua shells that have experienced water of lower pH (right) with shells maintained at present-day pH (left). The lower pH has resulted in shell erosion, lightening of shell and elongation of the respiratory pores.

Identifying the most vulnerable groups and species

It is highly unlikely that the changes in ocean properties, driven by climate change, will impact all marine life within the EEZ equally. Different groups (and different species within those groups) will exhibit a range of responses to modified ocean properties.

Vulnerability to change may manifest itself as slower growth and lower biomass, or in worst cases, reduced geographical distributions and even regional extinctions. Biota living at the edge of their environmental range could be particularly at risk as a small increase in ocean temperature or acidity could result in a rapid decline in growth rate.

The detection of such changes in health, growth rate, or biomass in the waters around New Zealand is not straightforward, as other factors, such as changes in fishing effort, year-to-year variability in fish recruitment, and/or the impacts of natural climatic variability (such as El Niño) could equally be responsible for such trends.



An idealised plot illustrating how an increase in temperature (red arrow) may reduce an organism's growth rate (dashed line) from present day optimal rates to a lower growth rate in the future, which may ultimately lead to extinction or migration.

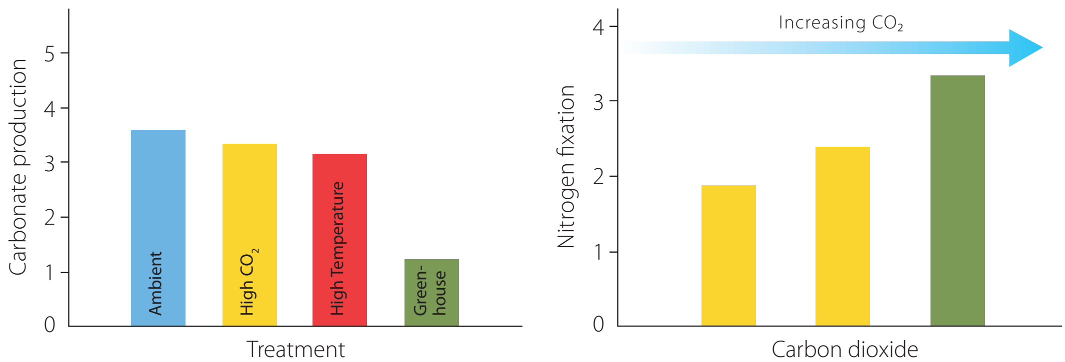
Assessing vulnerability

We can assess vulnerability using both direct and indirect approaches. Direct approaches include manipulation experiments and observations from natural ocean "laboratories". Manipulation experiments determine whether the alteration of an ocean property changes the performance of a particular organism. For example, at higher temperatures do organisms grow faster or slower? More than one property (for example, temperature plus CO_2) can be altered, which requires a more complex experimental design but may better simulate future oceanic conditions.

As we move up the food chain it becomes increasingly difficult to assess vulnerability using direct approaches as larger organisms are less readily manipulated in experiments and are influenced by more factors. We can use the ocean as a natural laboratory – for example by measuring how much the biota respond to changes in ocean properties over time, such as the supply of plant nutrients, during large-scale climate oscillations such as El Niño.

Indirect approaches include investigation of what sets the geographical boundaries on the distribution of a particular species. By comparing the distributions of different organisms and the regional properties associated with these distributions in both the modern ocean and geological ocean records (such as sediment and ice cores), it is possible to evaluate how their distribution may change in the future.

The life cycle of biota may hinder assessment of vulnerability. For example, hoki move between different water bodies during their life cycle. As climate change will alter the environmental properties of each water body differently, this may influence the degree of vulnerability to change at each life cycle stage.



The left figure shows the response of carbonate production by coccolithophore phytoplankton to temperature and high CO_2 separately, and together in a future "Greenhouse world". The right figure shows the change in nitrogen fixation by phytoplankton under increasing carbon dioxide.

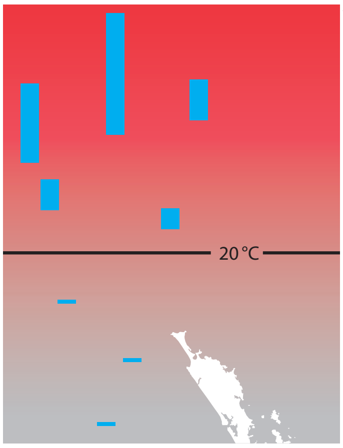
Predicting winners and losers of oceanic climate change

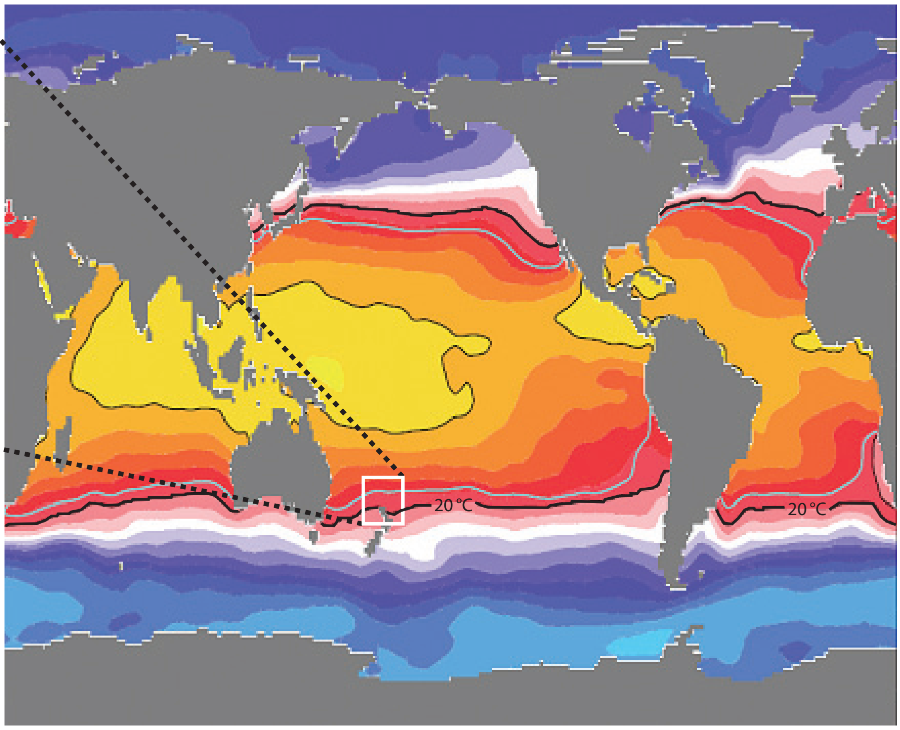
Some of the EEZ marine life may benefit under the altered oceanic conditions brought about by climate change, and others will decline. The resident biota may be affected by a single factor, such as temperature or a combination of factors, depending on their chemical make-up and trophic status. Consequently we cannot be sure which groups will decline and which will prosper.

In some cases the change may bring about positive consequences in terms of increasing the productivity, biomass, or diversity of a water body. For example, rising CO_2 and warmer temperatures may favour the growth of nitrogen fixers in the waters north of New Zealand, and regional warming may extend their distribution so that they become more prevalent in NZ waters.

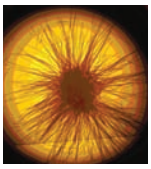
Calcifying organisms may be losers, particularly those in colder waters where carbonate availability is lower. This includes groups such as the pteropods (important planktonic molluscs in Southern Ocean food web) and corals – particularly cold water corals, which are most limited by carbonate availability.

Species within the same group can show both positive and negative responses to a change in pH or temperature. This may result in a change in species, but not necessarily in the loss or decline of a group in a particular area.





(Right) *The global map of ocean surface temperature, with the black line indicating the 20 °C isotherm which represents the southern boundary for nitrogen fixation by the phytoplankton Trichodesmium.*
(Above) *The inset shows the region north of New Zealand, where the rate of nitrogen fixation (indicated by the size of the blue bars) is only significant where surface waters exceed 20 °C. The southward migration of the 20 °C isotherm may see an increase in nitrogen fixation in New Zealand waters.*



Trichodesmium, *a nitrogen-fixing phytoplankton found in northern New Zealand waters.*

Using the Ocean Climate Change Atlas to predict how a species may be affected by climate change

Case study

Coccolithophores are phytoplankton which form blooms and whose productivity is thought to be influenced by factors including temperature, plant nutrients, irradiance, pH and CO_2 – all of which will be altered by climate change.

By comparing the panels below:

1. maps of the location of coccolithophore blooms for the EEZ (turquoise chalky waters in the satellite map), and

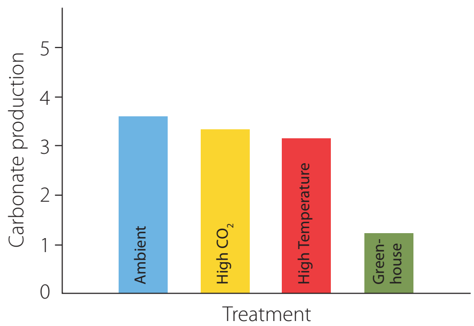
2. data from manipulation experiments in which coccolithophores were subjected to a matrix of treatments including warming and rising CO_2, and

3. climate model predictions of how surface seawater CO_2 concentrations in the EEZ will increase,

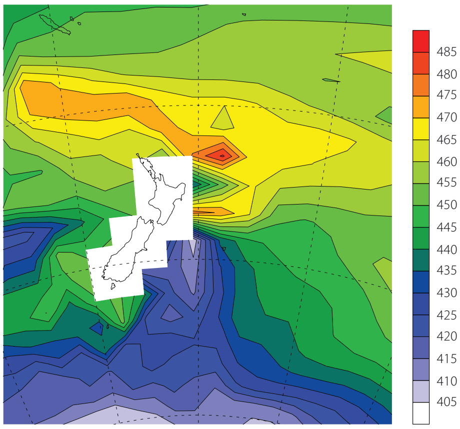
we can see how coccolithophores might be influenced by climate change.

1.

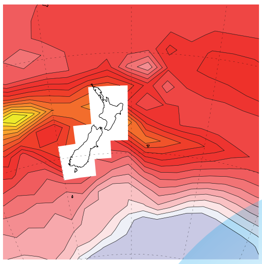
Coccolithophore

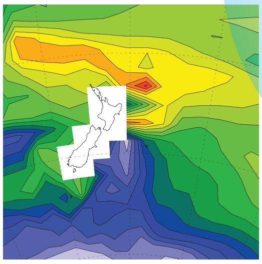


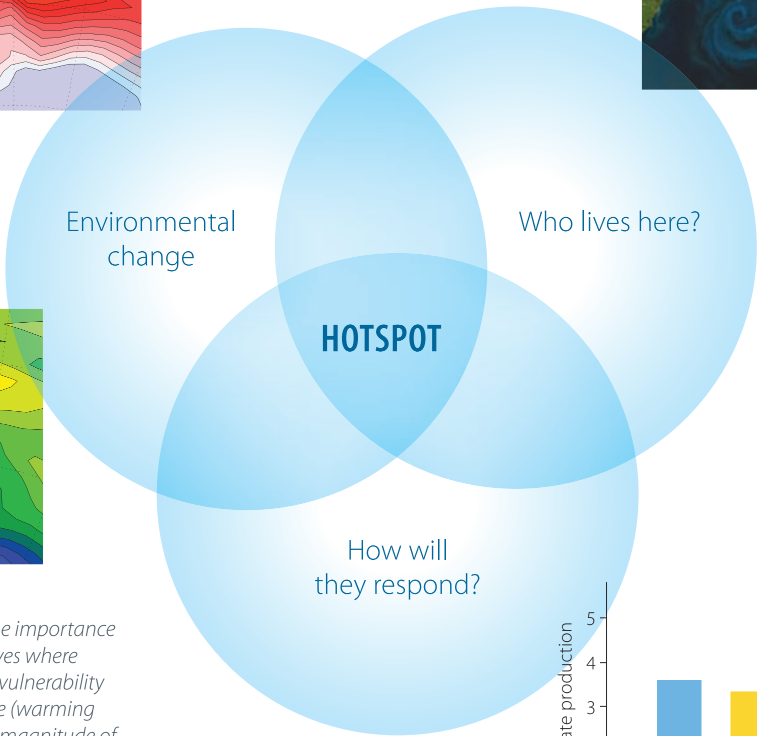
2.

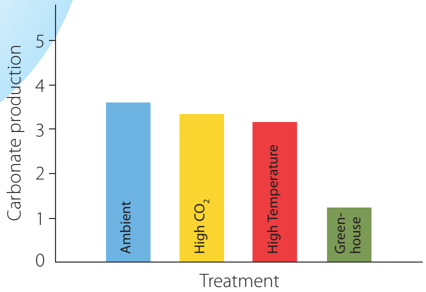


3. Difference in seawater CO_2 between 1990–99 and 2090–99.









Schematic to illustrate the importance of the interplay of who lives where (coccolithophores), their vulnerability to environmental change (warming and higher CO_2) and the magnitude of environmental change (warming & CO_2) which together will determine where in the NZ EEZ hotspots will occur, where there is likely to be pronounced alteration of the composition, diversity and/or productivity of ocean biota due to the effects of a changing climate.

Together, the information reveals that the combined increase in oceanic CO_2 concentrations and warming is likely to have a detrimental effect on coccolithophore blooms by reducing the degree to which they form their carbonate shells.

Thus, the atlas provides evidence of a specific region to the east of New Zealand where a particular phytoplankton group will likely be impacted by climate change.

This case study reveals how a complex issue or question can be visualised using the atlas format. In the near future the atlas will be available as a web-based tool, and it will be possible to investigate similar questions by linking distribution maps and experimental data from other groups or species from any trophic level.

Eventually we will be able to review the vulnerability of many of the marine resources within New Zealand's EEZ, providing valuable insight into the environmental and economic impacts of climate change on our oceans.

Development of the web-based Ocean Climate Change Atlas for New Zealand waters

This short publication is a primer that provides underpinning information on the principles on which the atlas is based. Within the next 12 months, we will make the transition to a web-based atlas. The atlas will be a living archive supplemented with additional information, for example on the distribution of species that have not previously been surveyed or mapped, or new experimental findings.

Such a web-based atlas can be used to explore the many permutations possible for a wide range of marine life across the EEZ. It will also reveal critical gaps in our knowledge that will require research efforts in the coming years. The existence of such a resource will also minimise overlap in research being carried out across the EEZ.

Other planned developments for the atlas in the next three to five years are to extend it from open ocean waters (at present the boundary for the climate model used in this Atlas Primer stops at around 50 km from shore) to coastal waters.

Given the close ties between climate and biodiversity/ecology, we also plan to make explicit links to national and international web-based repositories of such information, which NIWA currently either manages or contributes to, such as GBIF (Global Biodiversity Information Facility), OBIS (Ocean Biogeographic Information System), FBIS (NZ Freshwater Information System), etc.

Summary

- Climate change will alter multiple oceanic properties of the EEZ.
- The magnitude of these modifications will differ between water bodies.
- The response of the biota to altered water properties will range from positive, through no change, to negative impacts.
- Taken together, these modifications and the response of the biota will result in 'hotspots' – particular areas where pronounced change will occur.
- If such regions of the EEZ coincide with those which are pivotal for ecosystem services and/or for commercially harvested marine resources, this will have major ramifications for resource management and for our marine economy.
- At present, it is not known where, or how many, climate change 'hotspots' will arise, or how long they will persist for.
- The Ocean Climate Change Atlas can help frame the discussion and inform the investments that are needed to reduce uncertainties on the future of the biota of the EEZ in the face of climate change.

Acknowledgements

Thanks to:-

All from NIWA: Hoe Chang, Vonda Cummings , Kim Currie, Matt Dunn, Janet Grieve, Mark Hadfield, Rosie Hurst, Richard O'Driscoll, Harriet Palmer, Matt Pinkerton, Graham Rickard, Ashley Rowden, Karl Safi, Charlotte Severne, Jill Schwarz, Mark Tucker.

Mary Livingston (MFish), Scott Doney (Woods Hole Oceanographic Institution(WHOI), USA), Ivan Lima (WHOI, USA).

Image sources: Cover NASA/Orbimage, inset Hoe Chang (NIWA); Introduction Peter Marriott (NIWA); P2 Adapted from Carter et al 1998; P3 left and right panels, NASA/Orbimage, middle panel adapted from Sherlock et al, 2007; P4 NASA/Orbimage; phytoplankton images Mary Silver (UCSB, USA); Hoe Chang (NIWA), Karl Safi (NIWA); P6 upper panel NASA/Orbimage, lower left panel Ridgway (2007), middle panel Keith Hunter; (University of Otago); right panel Le Quéré et al. (2007); P7 schematic adapted from Ulf Riebesell (Kiel, Germany), zooplankton (Richardson, 2008); P8 based on Bradford-Grieve et al. (2003); P9 Rosie Hurst (NIWA); P.10 Net trawl Alan Blacklock; P11 left Bradford-Grieve (1994) and Vervoort (1957), right O'Driscoll (2003), bottom left Mark Ohman (SIO, USA); P12, P13 from Boyd et al (2008), P13 paua image Phil Heath; P15 left Feng et al. (2009), right Fu et al. (2008); P16 main image, Breitbarth et al. (2007); Inset data C. Law (NIWA) unpublished); image Karl Safi (NIWA); P17 image NASA/Orbimage, graph Feng et al. (2009), map Boyd et al. (2008), image Hoe Chang (NIWA); P.18 As on Pg 17.

References

Boyd, P.W. et al. 2008. Biogeosciences 5: 847– 864.

Bradford-Grieve, J.M. 1994. New Zealand Oceanographic Institute Memoir 102, 160 pp.

Bradford-Grieve, J.M. et al. 2003. Journal of Experimental Marine Biology and Ecology 289: 223-262.

Breitbarth E. et al. 2007. Biogeosciences 4:53–61.

Feng Y. et al. 2009. Mar. Ecol. Prog. Ser. 388: 13–25, doi:10.3354/meps08133.

Fu, F.-X. et al. 2008. Oceanogr. 53: 2472–2484.

Le Quéré et al. 2007. Science 22 June 2007:Vol. 316 no. 5832 pp. 1735-1738. DOI: 10.1126/science.1136188.

O'Driscoll, R. et al. 2003. NIWA Technical Report 119. 377 p.

Ridgway, K.R. 2007. Geophys. Res. Lett. 34: L13613, doi: 10.1029/2007GL030393, 2007.

Richardson, A.-J. 2008 Mar. Sci. 65 (3): 279-295. doi: 10.1093/icesjms/fsn028.

Sherlock, V. 2007. Journal of Geophysical Research - Oceans 112 (C6) Art No. C06010.

Vervoort, W. 1957. Report of the British, Australian and New Zealand Antarctic Research Expedition 1929-31, Report (series B No.3: 1-160 pp, figs 1-138).

Published by NIWA
Private Bag 14 901, Kilbirnie
Wellington, New Zealand

Citation: Boyd, P.W; Law, C.S. (2011)

An Ocean Climate Change Atlas for New Zealand waters

NIWA Information Series No. 79. 20p

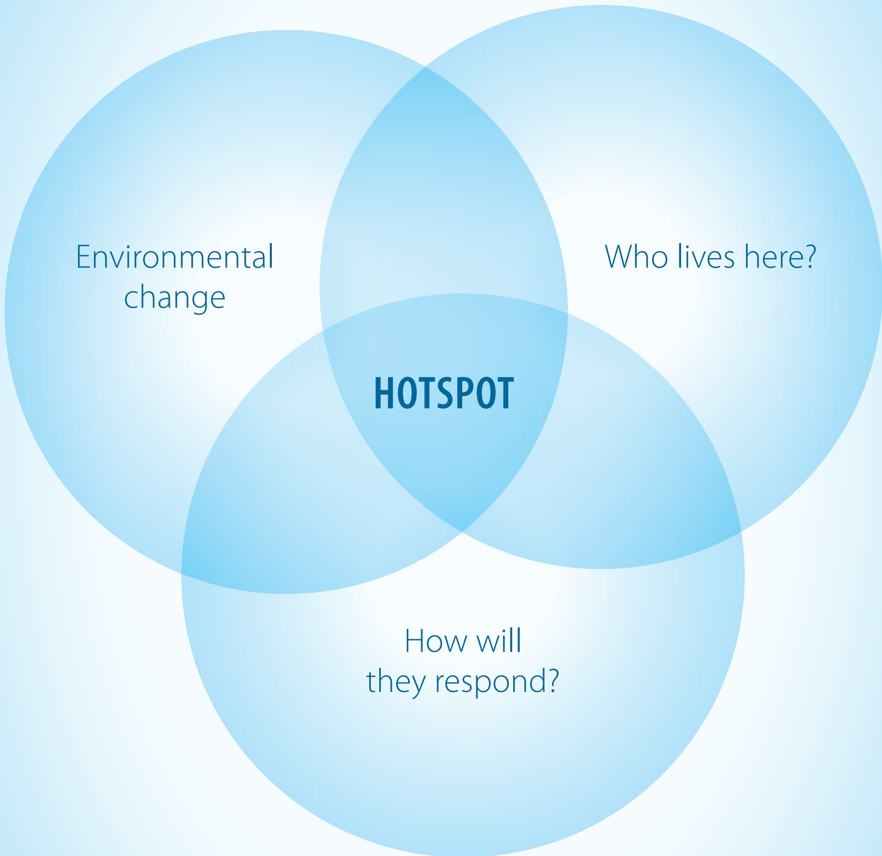
ISSN 1174-264X

Contact;

Dr Philip Boyd
p.boyd@chemistry.otago.ac.nz

Dr Cliff Law
c.law@niwa.co.nz

www.niwa.co.nz



enhancing the benefits of New Zealand's natural resources

NIWA
Taihoro Nukurangi