Climate Changes, Impacts and Implications for New Zealand to 2100

Synthesis Report: RA2 Marine Case Study

The NZ Exclusive Economic Zone and South West Pacific

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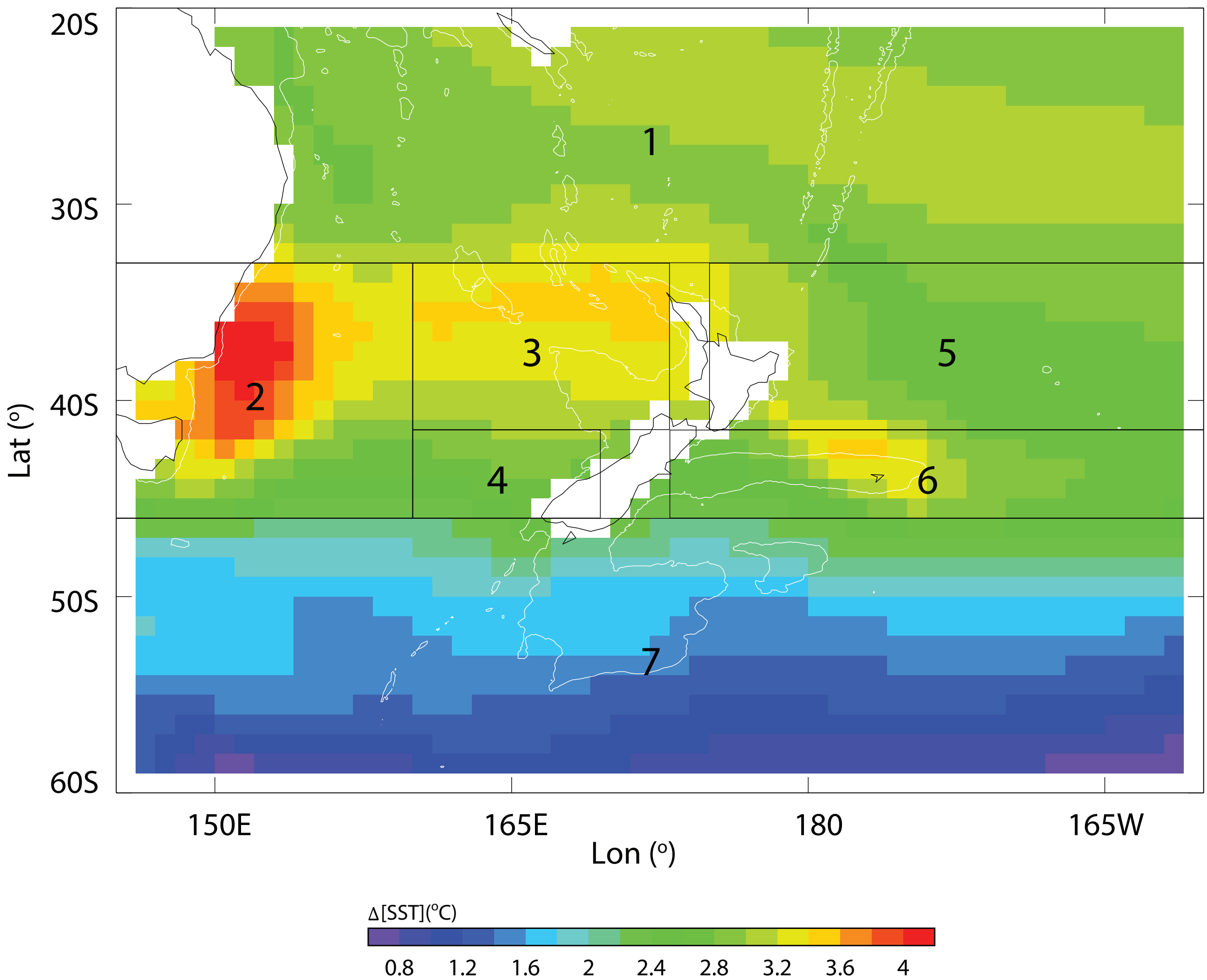
Projected change in Sea Surface Temperature for the end of the 21st Century under RCP8.5



HIGHLIGHTS

Projections from a suite of Earth System Models show significant changes in the open-ocean around New Zealand by the end of the 21st Century:

- Most of the ocean properties assessed are highly sensitive to future CO_2 emissions, with the high emission scenario (RCP8.5) yielding the largest projected changes.
- Mean sea surface temperature will increase by 2.5°C, and exceed 3°C in the north Tasman Sea. Decreases in surface chlorophyll-a, nitrate, phosphate and pH accompanied by shallowing of the surface layer.
- Projected changes in wave height are relatively small, with the largest increases (<+4%) in Subantarctic waters south of NZ, and decreases (-5%) in the Chatham Rise Region.
- Surface water nutrient concentrations will decline, particularly in the eastern Chatham Rise region, with a decrease in nitrate by ~9% under RCP8.5. Conversely dissolved iron is projected to increase in Subtropical water.
- The pH of surface water will decline by 0.33 under RCP8.5, with the resulting pH (7.77), and associated rate of change in pH, being unprecedented in the last 25 million years. Subantarctic surface pH will fall below the current pH minimum around 2030, with acidification creating corrosive conditions for organisms with carbonate shells in Subantarctic surface waters.
- Primary Production in surface waters will decline by an average 6% from the present day under RCP8.5, with Subtropical waters experiencing the largest decline.
- The decrease in particle flux from the surface to the seabed, of 9-12% by 2100, indicates that carbon sequestration will decline in the open ocean around New Zealand.
- Changes in particle flux will alter the food available for fish. A decline in particle flux was identified for all 38 species (including 30 commercial species), ranging from 2.2 to 24.6% by 2100. The largest decline in particle flux occurs in areas occupied by the northern spiny dogfish, gemfish, frostfish and tarakihi, and lowest decline in areas occupied by black oreo, barracouta, southern blue whiting and blue warehou.
- Climate change will not significantly lower dissolved oxygen in the mid-water around NZ, but the depth at which carbonate dissolves will become progressively more shallow. This will contribute to a decline in suitable habitat for cold water corals in New Zealand waters, and impact deep-sea ecosystems and biodiversity. The Chatham Rise may provide temporary refugia, which should be considered in spatial management of marine protected areas.
- The regional variation of the impact of climatic change in New Zealand waters needs to be considered in management and policy decisions. For example, regions projected to be most sensitive to climate change include Subantarctic waters south of 50°S and the eastern Chatham Rise, which support important fisheries, and Subtropical waters north-east of NZ.

INTRODUCTION AND BACKGROUND

The CCII project

The "Climate Changes, Impacts and Implications" (CCII) project is a four-year project (October 2012 – September 2016) designed to address the following question:

What are the predicted climatic conditions and assessed/ potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?

The CCII project brings together a strong research team with knowledge and modelling capabilities in climate, ecosystems, land and water use, economics, and sociocultural research to address the environment sector investment plan priority of "stronger prediction and modelling systems".

The project is based around five inter-related Research Aims (RAs) that will ultimately provide new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society. The five RAs are:

Research Aim 1: *Improved Climate Projections*

Research Aim 2: *Understanding Pressure Points, Critical Steps and Potential Responses*

Research Aim 3: *Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits*

Research Aim 4: *Enhancing Capacity and Increasing Coordination to Support Decision-making*

Research Aim 5: *Exploring Options for New Zealand in Different Changing Global Climates*

The overall purpose of RA2 is to: Perform five case studies on the potential impacts of climate change and other key drivers on alpine, hill & high country, lowland, coasts & estuaries, and marine environments. This synthesis report presents the results of the marine case study.

The marine case study

There is growing awareness that climate change is altering the physical and biogeochemical nature of the open ocean with impacts on, and implications for, marine ecosystems and the socio-economic benefits and ecosystems services we gain from the ocean (Bopp et al, 2013; Weatherdon et al, 2016). The recent IPCC assessment identified that current and projected changes in ocean properties are unprecedented in relation to past records (Pörtner et al, 2014), raising concerns regarding the capacity of marine ecosystems to cope with the rapid rate of change. The oceans contain 93% of the additional heat retained by the globe (Levitus et al, 2012) arising from increasing greenhouse gas concentrations, and so increasing ocean temperature is a primary feature of climate change in marine ecosystems.

Warming and major changes in current flow have already resulted in regional shifts in the abundance and distribution of a number of different marine biotic groups (Poloczanska et al, 2013). The observed poleward migration of species may result in major changes in ecosystems and species interactions in some locations, with negative impacts on food and economic security in tropical and Subtropical regions (Hoegh-Guldberg et al, 2014). Warming also increases density stratification in the upper-ocean, which affects mixing, light availability and nutrient supply. The resulting interaction of these changes will alter phytoplankton productivity, distribution and biodiversity and impact marine foodwebs via changes in the quantity and quality of organic matter, with implications for ecosystems, fisheries and the ocean CO_2 sink. In addition warmer temperatures reduce the dissolved oxygen-carrying capacity of water and accelerate biological oxygen consumption. The uptake of anthropogenic CO_2 also leads to ocean acidification, which is causing changes in water chemistry and pH that impact a variety of biological groups, particularly carbonate-forming organisms and algae, and influencing marine ecosystem productivity and biodiversity.

As with the global ocean, the South West Pacific (SWP) will be influenced by climate change. New Zealand (NZ) straddles the boundary between Subtropical and Subantarctic water masses, with its climate influenced by the Tasman Sea, and the Southern Ocean, and so it is currently unclear how the NZ Exclusive Economic Zone (EEZ) will respond to climate change. For example, warming and change in currents may increase the presence of warmer low-productivity water in the EEZ, whereas a poleward shift in primary production and species distribution may be beneficial in temperate and Subantarctic waters around NZ (Cheung et al, 2010). Information on the potential future changes in NZ waters is then critical to inform mitigation and adaptation approaches, and for robust ecosystem management of our ocean.

STAKEHOLDER ENGAGEMENT AND CASE STUDY SELECTION

The objectives of the CCII marine case study were directed by national requirements and concerns, established with marine stakeholder organisations via three fora:

i) presentations and discussions at the annual CCII All-In Workshops;

ii) individual meetings with stakeholders; and

iii) a marine stakeholders workshop, including representatives of MPI (Policy and Fisheries), Te Ohu Kaimoana, MfE, EPA, DoC, ECO, Statistics NZ, and the Paua Industry Council.

Predicting the future dynamics of the ocean and associated status of marine foodwebs and ecosystems is central to effective sustainable resource use and management of fisheries, extractive industries, and other ecosystem services. However there is currently a lack of climate change information input to planning and management across the NZ marine sector. Context relevant information is required on decadal (accommodating climate variability and stakeholder planning cycles) to millennial timescales, and also spatially to identify the most vulnerable habitats and regions. Key drivers of change and a range of different scenarios need to be considered in decisions and actions, to establish risk and operational implications of climate change, and to determine where, when and how data collection, modelling and adaptation will be most effective.

Key issues for seafood stakeholders include how changes in marine primary productivity and the lower foodweb, and also species range shifts, will affect commercial fish stocks. The long term viability and sustainability of fisheries is particularly important to Māori, who own 50% of New Zealand's wild fishing quota. Projections are required by MPI for stock assessment and decisions on Total Allowable Catch, particularly related to which Quota Management Systems, protection zones and species will be most affected by climate change. Information is also needed to assess the relative, and combined, impacts of fishing and climate change, and for spatial management including location of Benthic Protection Areas. Projections will inform on the need for and type of adaptation, monitoring and research requirements, and the inclusion of fisheries-relevant climate and environmental indices in fisheries analyses. Both DoC and MPI have responsibilities for protected species and ecosystems, and so require information on how climate change will impact areas of ecological significance and marine reserves. In addition, DoC and EPA need to consider climate change impacts in decisions on marine resource extraction and consents.

The aim of the CCII marine case study was to generate projections of future conditions in waters of the SWP, and specifically the NZ EEZ. As regional models of suitable complexity are not yet available for the SWP, global Earth System models were evaluated and applied for regional projections. The study initially assessed the skill of these global models to describe the present state of the SWP, by validating the model outputs against observational datasets for selected variables. Having established the optimal model suite, model outputs were then generated for two future periods and compared to present day data, to assess the projected change for a number of climate-sensitive physical and biogeochemical variables. Discussions with stakeholders directed the research towards establishing future change in three biotic groups: phytoplankton, cold water corals and fish, with the projections used to assess the implications for their future distribution and abundance.

The projections underpin predictions of the future state of open-ocean ecosystems in the EEZ, and provide insight into the implications of climate change on marine biodiversity, productivity and socio-economic sustainability, with the additional aim of informing national marine policy and management. In addition, the projections provide information for the design of experiments examining the impacts of climate change on natural systems. This synthesis of the CCII marine case study also delivers a Climate Change Atlas for NZ waters, as introduced in Law & Boyd (2011).

METHODOLOGY/APPROACH

Future concentration scenarios

The Representative Concentration Pathways (RCPs, van Vuuren et al, 2011), are used to generate future projections of environmental conditions. The RCPs represent estimated changes in radiative forcing resulting from greenhouse gas concentration trajectories under different socio-economic assumptions. The RCPs describe four potential climate futures (see Appendix Figure 1); RCP2.6 represents a low-emission mitigation pathway, requiring removal to achieve a decline in atmospheric CO_2 by 2050, whereas RCP8.5 is the high emission scenario. The two middle pathways (RCP4.5 and 6.0) require stabilisation of emissions at different timepoints during the 21st Century. Projections in this report are generated primarily for RCP4.5 and 8.5, although results for all four RCPs are included for the marine carbonate system and ocean acidification.

Earth System Model validation for the NZ EEZ region

Regional models that incorporate hydrodynamics and biogeochemistry are unavailable for the SWP, and so the best alternative approach for projecting future conditions in the NZ EEZ is to use the outputs of global Earth System models. The Coupled Model Intercomparison Project 5 (CMIP5) is an international project that stores output from a number of these global models. Prior to each IPCC report each model centre generates a suite of simulations following a common protocol (Taylor et al, 2012), which includes a present-day simulation, and future projections under different concentration scenarios.

The CMIP5 provides the opportunity for comparison of the effectiveness of different models to simulate conditions in the NZ region. Of the ~50 models in the CMIP archive, only 16 include marine biogeochemical cycling, and only six of these include the carbonate system (see Appendix Table 1). An assessment was carried out to determine how robust the outputs of each of the 16 models were for the SWP, by comparing their outputs for the present-day with observations for different variables. The "Inner" ensemble were the group of models that best fitted the observations, and the "Outer" ensemble the less accurate fits (see Appendix Figure 2). The rationale here is that the Inner models which best describe present-day conditions are more likely to better describe future changes. The model fits and ranking methodology are described in the Appendix, and detailed in Rickard et al (2016).The importance of validation and identification of the best models, is demonstrated for surface chlorophyll-a (a photosynthetic pigment, which is an indicator of phytoplankton biomass) in Appendix Figure 3.

Scope of the study

Data are presented for each variable for three time periods, in keeping with the CMIP5 models:

- Present-day: the 30-year period between 1976 and 2005
- Mid-Century: future projections of annual and monthly mean for 2036 to 2055
- End-Century: future projections of annual and monthly mean for 2081 to 2100.

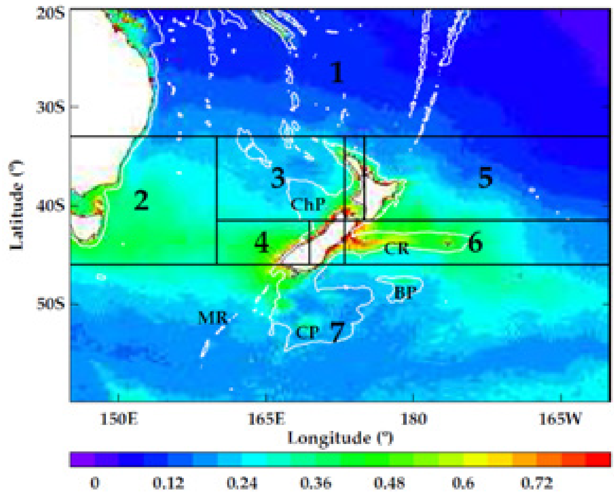


Figure 1. Map of the case study region, the South west Pacific, with sub-regions indicated by boundaries and region numbers, overlain on the mean surface chlorophyll-a (mg Chl m^{-3}) (Rickard et al, 2016).

The regional scope of the study encompasses the SWP between 145°E to 160°W and 60°S to 20°S, and incorporates the NZ EEZ. As there are complex responses to climate change at regional scales (Boyd et al, 2015) the study region is divided into seven sub-regions (Rickard et al, 2016). Regions 1-5 contain Subtropical water (Chiswell et al, 2013), region 6 includes the Subtropical Front over the Chatham Rise, and region 7 includes Subantarctic and polar water. As the spatial resolution of the global models is 1 degree, this does not provide sufficient resolution to accommodate the physical and biogeochemical gradients found in coastal regions, so these regions are omitted from the analysis. As a result the impacts of climate change on aquaculture, invasive species, land-ocean interactions, and aesthetic values/tourism are excluded in the present study.

The model projections are presented using three different formats:-

a) Mean values from the Inner and Outer ensembles, and also individual model values, for the Mid- and End-Century;

b) Temporal changes in mean values from present day to 2100; and

c) Maps of the regional variation in change in the SWP

Significant change in a variable is defined by two criteria:

a) The magnitude of the model mean change is greater than the inter-model standard deviation (spread); and

b) 80% of the models agree on the sign of the mean change.

Below we describe the projections for each variable, and the associated implications. Note that for certain variables, such as significant wave height, particle flux and fluxFish, different modelling approaches and regions are used, as described in the Appendix.

RESULTS AND DISCUSSION

Physical variables

Sea Surface Temperature (SST)

Changes in the temperature of the surface ocean are already evident globally, although there is significant regional variation in the degree of warming. Projections for the SWP show an increase in SST by Mid- and End-Century, regardless of RCP and model (see Figure 2A). The mean increase is ~1°C by Mid-Century, and ~2.5°C by End-Century for RCP8.5, with the latter representing a 16% increase relative to present day SST. There is no significant difference in SST for the Inner and Outer ensembles under RCP4.5, with a mean difference of <0.2°C and a range of 1°C for all models by End-Century. However there is greater variation under RCP8.5, approaching 2°C, across all models by End-Century (see Figure 2A).

Figure 2B shows the spatial variation of change in SST for End-Century under RCP8.5, with surface warming across the entire SWP. The most striking feature is the strong warming of +4°C in the western Tasman Sea associated with the southerly penetration of the East Australian Current off south-east Australia in region 2 (Ridgway, 2007). This region is warming at a rate four times that of the global average as a result

A

B

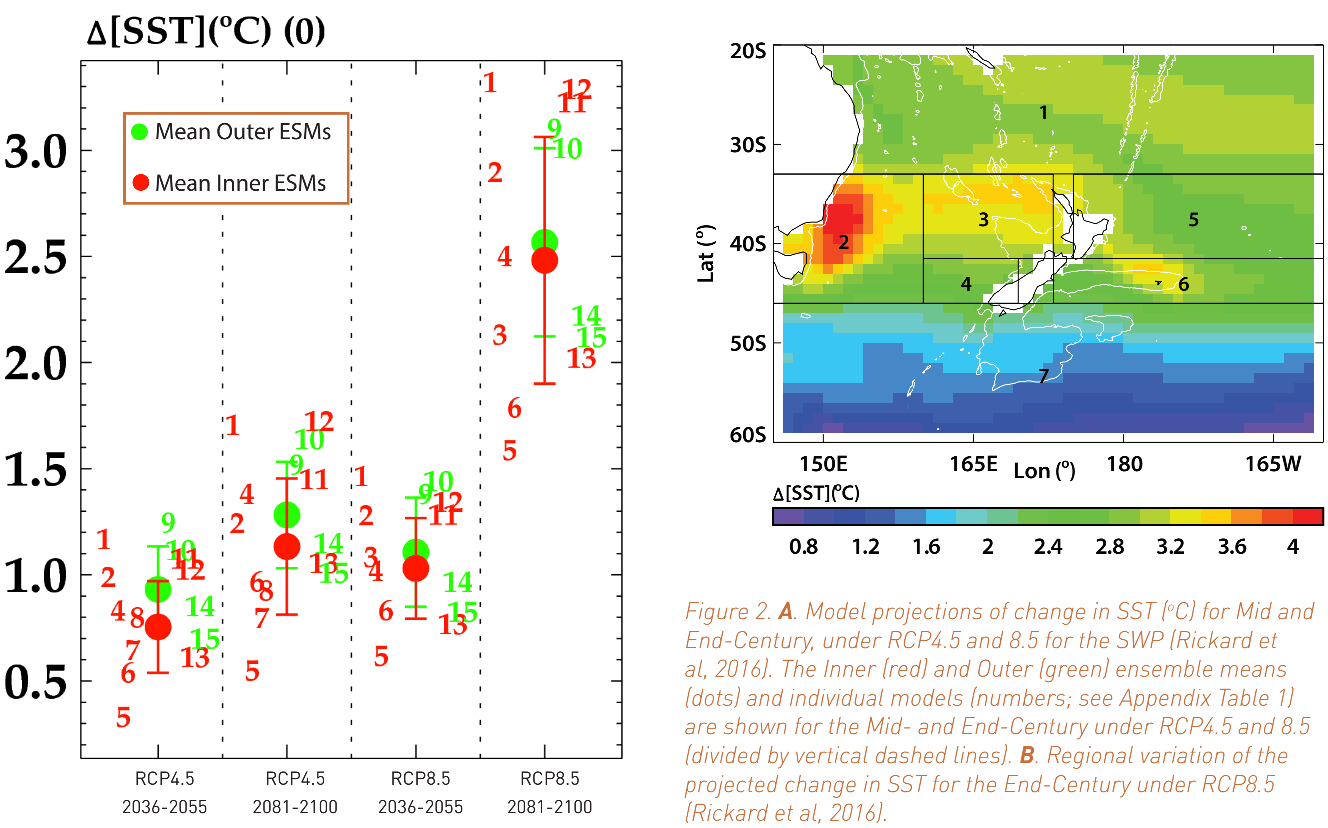


*Figure 2. **A**. Model projections of change in SST (°C) for Mid and End-Century, under RCP4.5 and 8.5 for the SWP (Rickard et al, 2016). The Inner (red) and Outer (green) ensemble means (dots) and individual models (numbers; see Appendix Table 1) are shown for the Mid- and End-Century under RCP4.5 and 8.5 (divided by vertical dashed lines). **B**. Regional variation of the projected change in SST for the End-Century under RCP8.5 (Rickard et al, 2016).*

of the climate-driven spin-up of the South Pacific gyre (Roemmich et al, 2016), driving regional change in marine ecosystems with a reduction in temperate species, increase in sub-tropical species and shift towards nutrient-poor conditions (Frusher et al, 2014). Warming transfers across the northern Tasman Sea along 35°S in region 3 in association with the Tasman Front, resulting in the most significant regional SST increase in the NZ EEZ (Figure 2B). Although no temperature change was observed during the 1990's, surface warming in the Tasman Sea has been observed more recently (P. Sutton, pers. comm.). Warming of >2.5°C is also evident in the eastern Chatham Rise (region 6) by End-Century, whereas warming is lowest in Subantarctic waters in region 7 (see Figures 2B and 3A).

The largest absolute temperature change occurs in the Tasman Sea in regions 2 and 3 under both scenarios and both timeframes, with warming exceeding 3.1°C by End Century under RCP8.5 (see Figure 3A). However a different regional trend is apparent in proportional temperature change, being similar in most regions by End-Century (16-20%), but with Subtropical water in region 1 showing lower proportional warming, relative to the regional average of 16% (see Figure 3B). The timeline of the deviation in projected SST from the present-day range is shown across the 21st Century in Appendix Figure 4.

Implications – The projected warming of 2.5°C suggests that NZ waters may be progressively influenced by subtropical water species and biogeochemical conditions over the 21st Century. The SW Tasman Sea has been warming at a similar rate (2.3°C/century; Ridgway et al, 2007) to that projected for rest of the SWP; using this region as a potential analogue suggests future decline in primary productivity and loss of temperate water species in NZ waters.

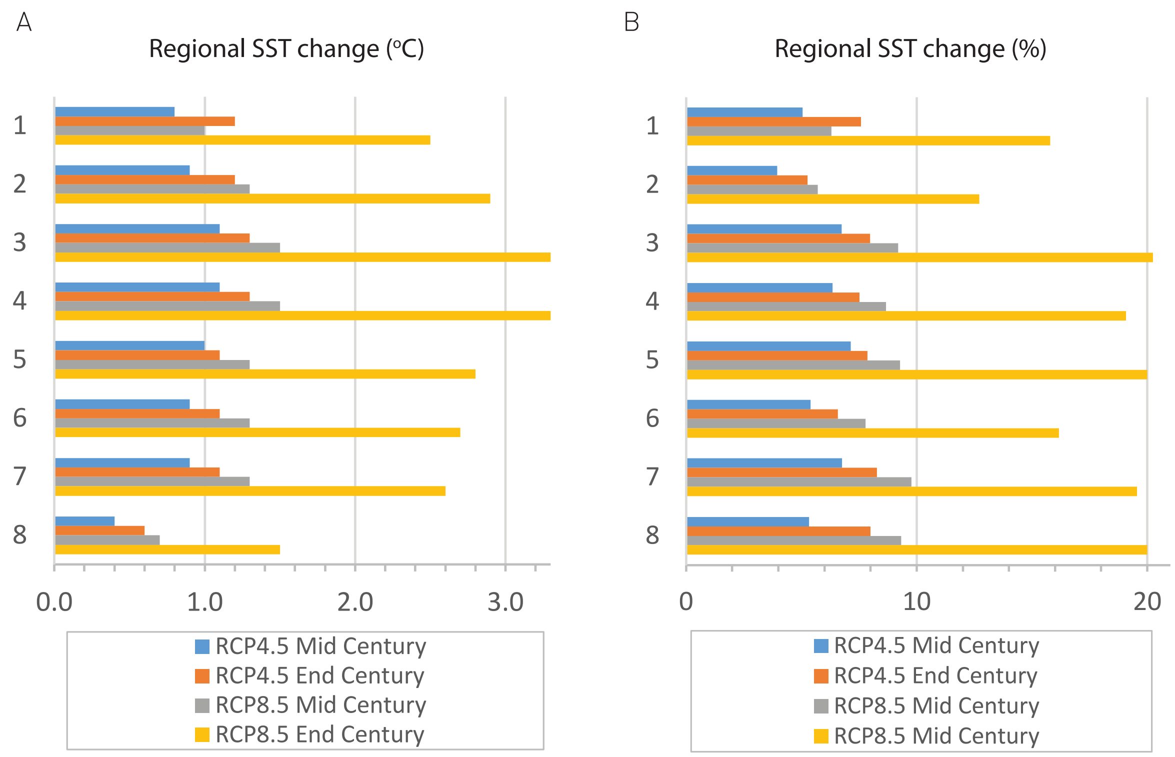


*Figure 3. Changes in projected SST presented as **A**. absolute change (Δ,°C), and **B**. proportional (%) change, for Mid and End-Century for RCP4.5 and 8.5. Note that 0 refers to the entire SWP region in Figure 1.*

Surface Layer Depth

Virtually all primary productivity in the ocean occurs in the sunlit surface layer, and relies on nutrients supplied by diffusion from deeper waters. An increase in the temperature of the surface ocean will result in a shallower surface layer but will also increase the density gradient at the base of the surface layer, causing a reduction in exchange and nutrient supply. Whereas phytoplankton may benefit from a warmer, shallower surface layer due to higher light availability, the decrease in nutrient supply may limit their growth.

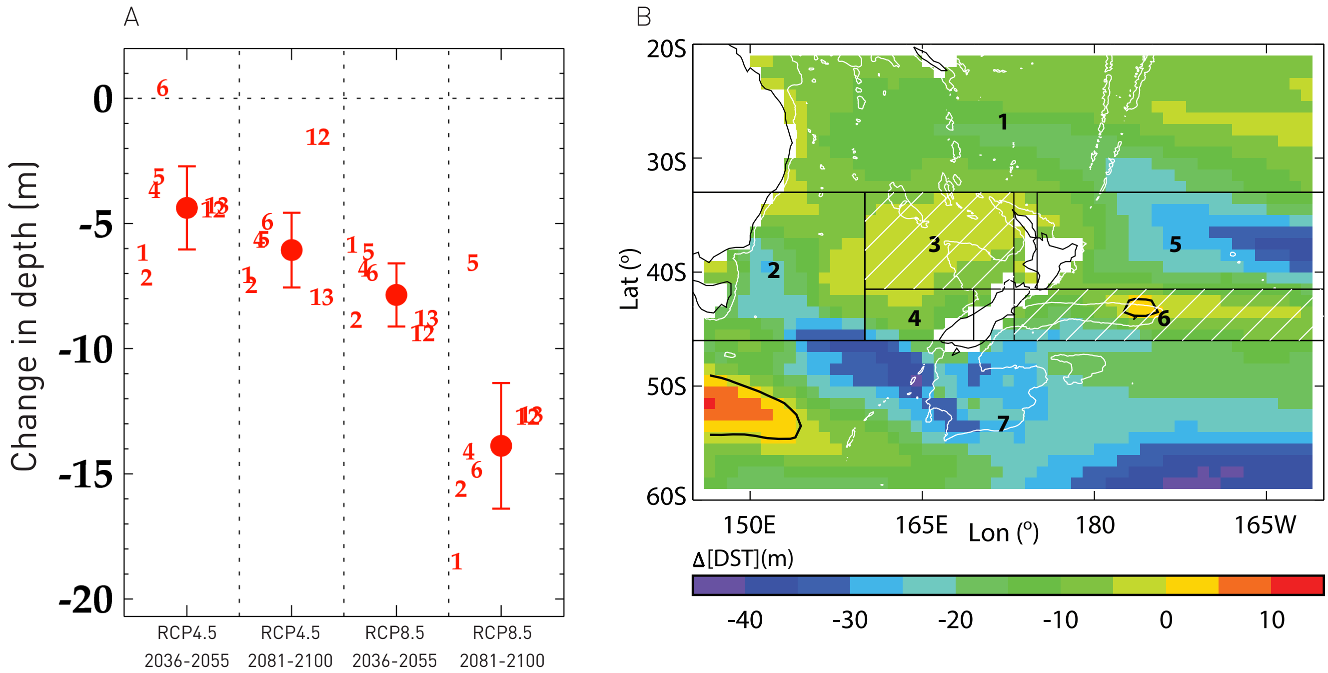


*Figure 4. **A**. Projected change in the depth of the surface layer (metres), where negative values indicate a shallower layer, for Mid and End-Century under RCP4.5 and 8.5 (separated by vertical dashed lines), respectively) for the Inner model ensemble in the SWP. (Rickard et al, 2016). The horizontal dashed line indicates zero change in depth, **B**. shows the regional variation in projected changes in surface layer depth (ΔDST) for End-Century under RCP8.5, with the hatching indicating no significant change (see Appendix for definition).*

All models show a decrease in the depth of the surface layer and, despite discrepancies in certain models, there is no significant difference in change projected by the Outer and Inner ensemble (data not shown). The depth of the surface layer varies seasonally and regionally, with a current range from 10m in sub-tropical waters in spring and summer, to greater than 250m in winter in the NZ region (S. Nodder, pers. comm.). Surface layer depth is projected to decrease by ~6m by End-Century under RCP4.5, and by ~14.2m under RCP8.5, across the SWP, (with a mean decrease of 15.4%, (see Figure 4A). Regionally, the most significant change in surface layer depth is in Subantarctic waters south of NZ in region 7, with the surface layer shallowing by 30-40m, although significant shoaling is also apparent in the Subtropical gyre in region 5 (see Figure 4B).

Implications – The impact of surface layer shoaling may differ for different water masses. A shallower surface layer may benefit phytoplankton, and so productivity, in colder Subantarctic waters, as this will increase light availability for growth. Nutrient concentrations are relatively high in Subantarctic surface waters, and so a decrease in vertical supply will have less impact. However, the shallow surface layer in sub-tropical waters already experiences high light and low nutrients, and so a further decrease in vertical nutrient supply will further reduce productivity (Riebesell et al, 2009). Consequently future warmer, shallower surface layers may have positive effects on primary productivity in southern NZ waters, but negative effects in warmer subtropical waters.

Significant wave height

Projections of future wave climate were generated using a different approach to the parameters above, with IPCC AR4 scenarios (Nakicenovic and Swart, 2000) also used in addition to the RCPs (see Appendix). Currently highest wave energies occur south of NZ, generated by consistently strong winds in the Southern Ocean, with the swell from the south progressively moderated by the sheltering effect of the NZ land mass (Figure 5A). Figure 5B shows the projected percentage change in significant wave height by the late 21st Century under the moderate concentration scenario, with a minor (1-3%) increase south and west of the South Island, and moderate decreases northeast of the North Island. Figure 5C shows the corresponding changes under the higher-concentration AR4 A2 scenario, of similar spatial pattern but greater magnitude, with an area of increased wave height extending further south-east of the South Island. For comparison, Figures 5D and 5E show the projected change under RCP4.5 and RCP8.5, respectively, with a consistent meridional trend of increasing wave height south of New Zealand, and decreases to the northeast.

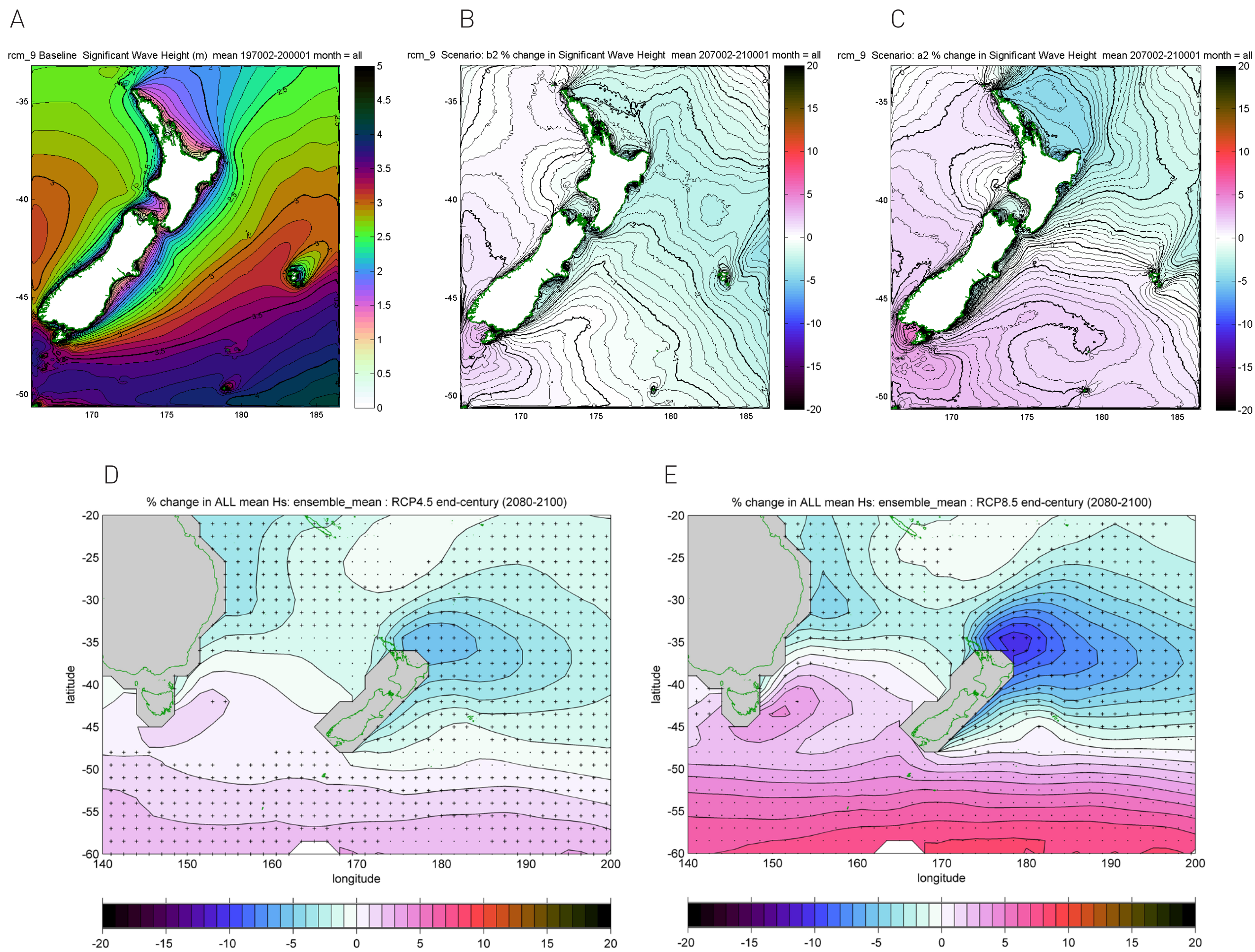


*Figure 5. **A**. Present-day mean significant wave height, and percentage change in mean significant wave height for the end of the 21st Century under **B**. moderate emision scenario B2 and **C**. the higher emission senario, A2, relative to present-day (see Appendix for details). Mean percentage change in significant wave height is also shown for **D**. RCP4.5 and **E**. RCP8.5 for End-Century relative to present day. The heavy- and lightly-stippled areas indicate respectively where all four, and three out of four, ensemble models show the same sign of change as the ensemble mean, and so indicate greater confidence in projections.*

On a global basis all simulations predict a small net decrease in global averaged significant wave height, with a range of -0.64% to -1.1%, depending on scenario, by the end of the 21st Century. However, there is considerable variability between simulations in the magnitude and sign of the net change around NZ, due to the region straddling regions of positive and negative projected change. The regional variation in projected mean wave height for the Mid- and End-Century is presented in Appendix Table 2. Overall projected changes for the NZ region are consistent with global projections, except for Subantarctic waters (region 7) where projected increases are greater. Region 7 also shows the largest increase in significant mean wave height in the EEZ, although the proportional change is less than 4% (0.14m), even in the most extreme case (RCP8.5 End-Century). Conversely region 5 shows a significant decrease in projected significant wave height of 5.3% (0.13m) under RCP8.5 by End-Century. Projected proportional change is greater in other regions of the global ocean, with wave height increases of ~10% in the central tropical South Pacific, and decreases of ~15% in the North Atlantic.

Wave climate is of significance to commercial vessel operators, and each vessel carrying out a particular operation will generally have set limits on environmental conditions under which it can carry out that operation. While subtle changes in mean wave climate will not impact the viability of marine operations, the occurrence of more energetic conditions may be of concern. Figure 6A maps the percentage of time that significant wave height exceeds 5.0 m, under the simulated present-day period which, like the mean wave height in Figure 5A, shows highest values in the south, decreasing northward. The projected changes in exceedance of the 5m threshold relative to present-day (Figs 6B and C) show increases south of NZ in both scenarios, in line with expected shifts in mean wave climate. However, in contrast to projected shifts in mean wave height (Figure 5B and C), there are no decreases in 5m threshold exceedances northeast of the North Island, and there is even a small increase under the B2 scenario.

Implications – Projected changes in significant wave height by 2100 are relatively low, with the largest increases of <4% in Subantarctic waters south of NZ, and decreases of 5% on the Chatham Rise. Similar trends are projected for 5.0 m wave height exceedance, although vessel operators should consider the projected increases in 5.0 m wave height exceedance of 14-20% for waters south of the South Island by End-Century.

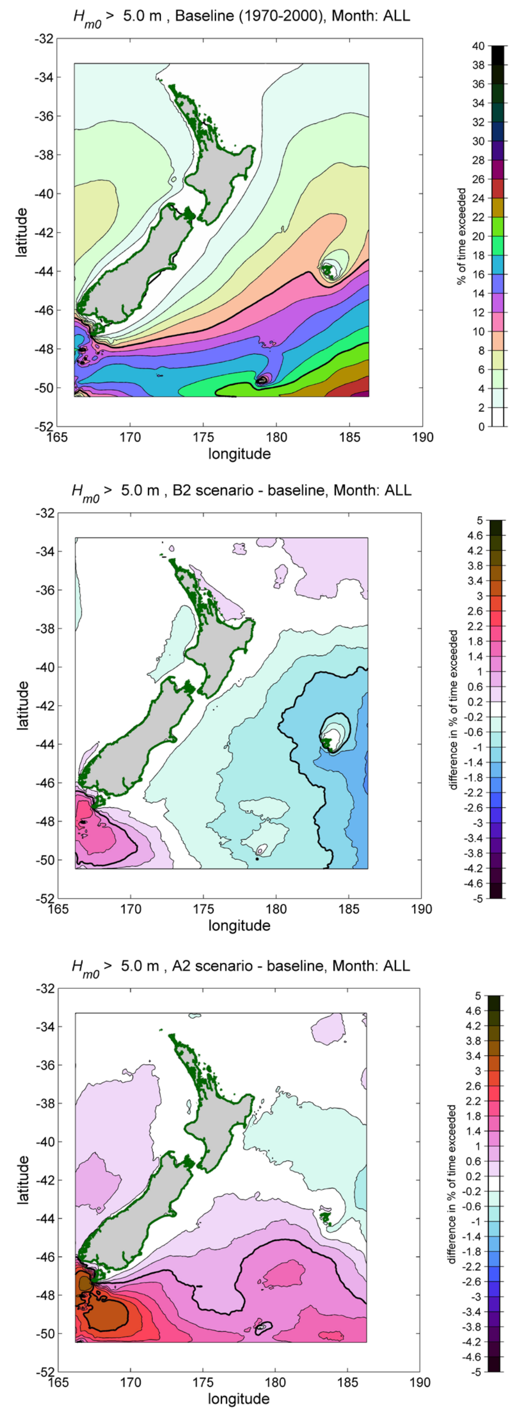


*Figure 6. **A**. Mean percentage of time that significant wave height exceeds 5.0m for the present day, and change in the percentage of time (averaged over the full simulation) that significant wave height is expected to exceed 5.0m, for **B**. moderate emision scenario B2 and **C**. the higher emission senario, A2, for End-Century relative to present-day.*

Biogeochemical variables

Nutrients

The availability of nutrients is critical for phytoplankton growth. For example, waters characterised by low concentrations of macronutrients (nitrate, phosphate and silicate), support low phytoplankton biomass and productivity and lower carbon export to the deep ocean per unit area. Conversely, regions of high surface macronutrient concentrations are characterised by high plankton productivity and more productive fisheries, such as the Subtropical Front water in the Chatham Rise region. One notable exception in NZ waters are the high nutrient-low chlorophyll Subantarctic waters to the southeast, where phytoplankton growth is limited by low dissolved iron (Boyd et al, 1999).

No significant change is projected for macronutrient concentrations by Mid-Century, but there is a significant decline by End-Century under both RCP4.5 and 8.5 (see Figure 7A-C). Although there is scatter in the projections by different models, with some indicating an increase in future concentrations, the Inner ensemble mean shows a decline from present-day, of ~0.5 (9.2%) and 0.04 (7.8%) mmol/m^3 in nitrate and phosphate concentrations, respectively by End-Century under RCP8.5. As with other variables, the projected change by the End Century under RCP4.5 is similar to that projected for Mid-Century under RCP8.5, emphasising the sensitivity to future CO_2 emissions. Projections indicate an overall decline in mean silicate concentration, of 0.18 mmol m^{-3}, which is 5.6% of present-day concentrations. Conversely, dissolved iron, which is an important micronutrient, increases under both RCPs by 0.03 mmol m^{-3} by End-Century under RCP8.5, equivalent to 24% of present-day mean concentrations (Figure 7D).

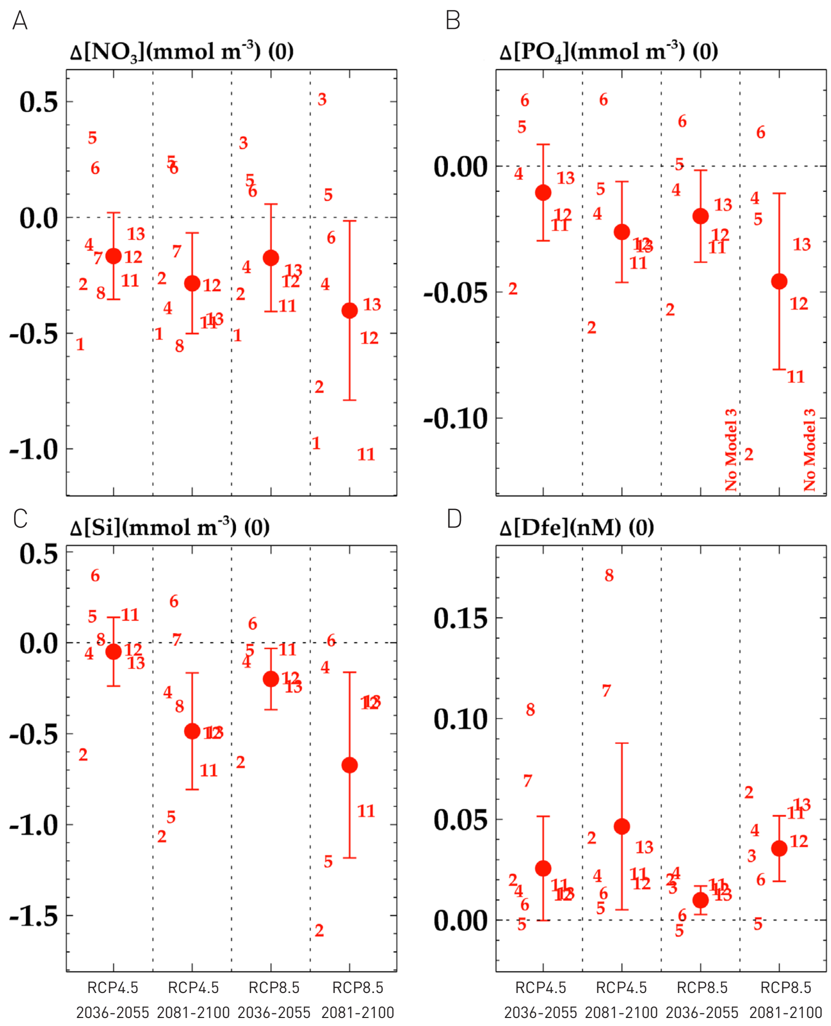


*Figure 7. Projections of change (Δ) in dissolved surface nutrient concentrations for **A**. nitrate, **B**. phosphate, **C**. silicate, and **D**. iron from the Inner ensemble, with individual model values indicated by number (see Appendix Table 1), and the filled circles the ensemble mean. Negative values indicate a decrease in concentration, and positive values an increase in concentration. Vertical dashed lines separate the different projections for Mid- and End-Century under RCP4.5 and 8.5, and the horizontal dashed line indicates zero change in concentration (Rickard et al, 2016).*

Projected changes in concentrations of the three macronutrients show similar spatial distributions around NZ, with the most significant declines on the eastern Chatham Rise in region 5 under RCP8.5 by End-Century (Figure 8). Declines in concentration are also projected in region 2 associated with the East Australian Current. Conversely all three macronutrients increase in Subantarctic water south-east of New Zealand, although this result is non-significant due to the variation in model outputs. The spatial change in iron concentration shows a clear dichotomy between the two major water masses, with minor non-significant change in Subantarctic water, and an increase in Subtropical water that is largest (+0.12 mmol m^{-3}) in region 2 in the SW Tasman Sea.

Implications - The projected changes in nutrient availability may alter regional productivity and foodwebs. Globally there is evidence that oligotrophic (low-nutrient) waters are expanding, in response to warming (Polovinia et al, 2004) and, as 50% of NZ waters are, at least seasonally, oligotrophic then future decreases in macronutrient availability may reduce productivity in the EEZ. The Chatham Rise is the most productive region in NZ waters, and the projected decline in macronutrients may have ramifications for fisheries in this region. Conversely an increase in iron availability in warmer Subtropical waters, particularly the Tasman Sea region, may increase regional primary productivity, but this is unlikely to offset the overall decline in primary productivity in NZ waters by End-Century.

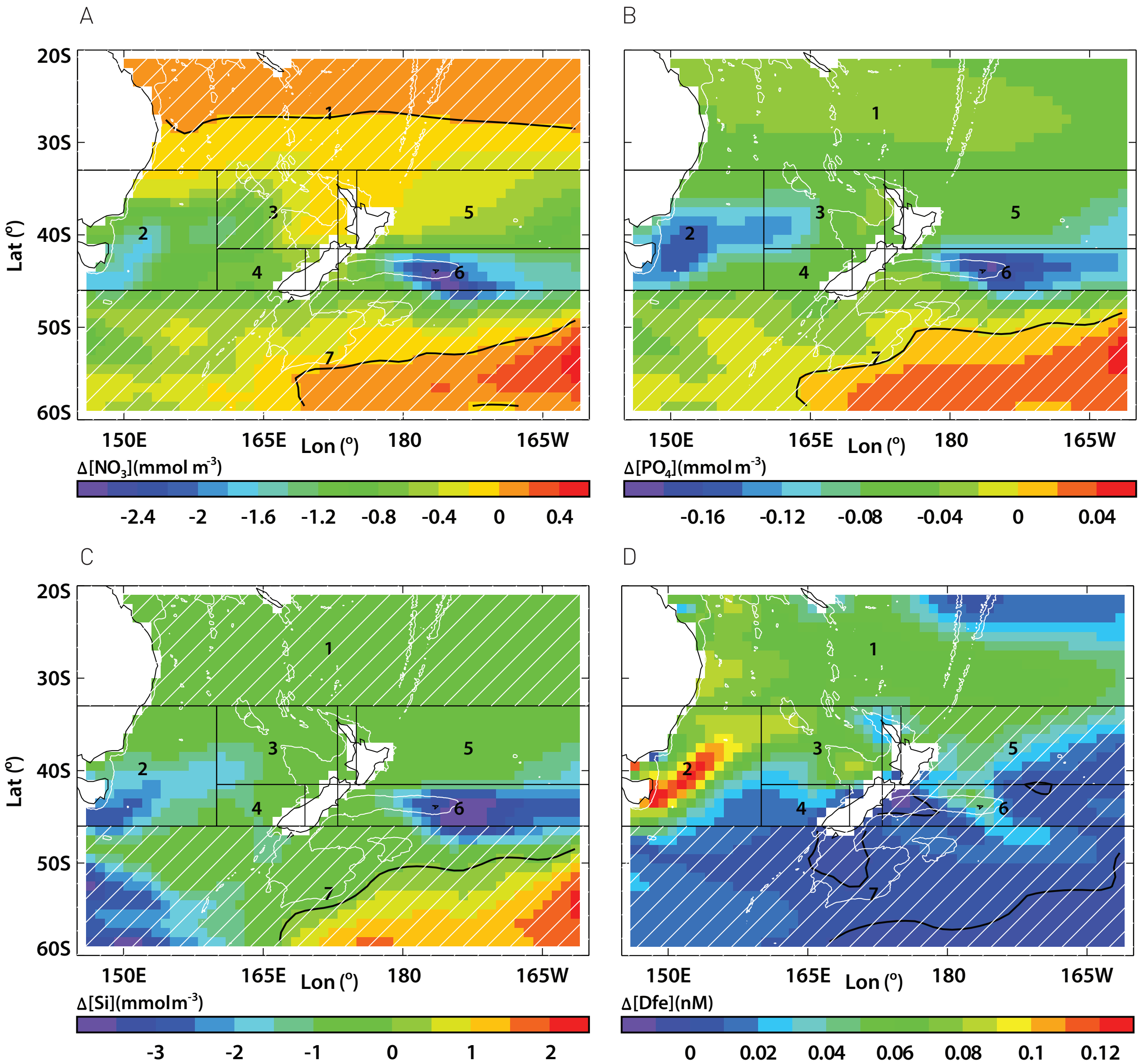


*Figure 8. Inner ensemble projections of change (Δ) in surface water concentrations of **A**. nitrate, **B**. phosphate, **C**. silicate, and **D**. iron, for End-Century under RCP8.5. Black contours indicate zero change, and white contours the 1000 metre isobath. Regions are hatched where the change is not significant (Rickard et al, 2016).*

The carbonate system and ocean acidification

The transfer of anthropogenic CO_2 into the ocean is altering the oceans carbonate buffering system, lowering pH and carbonate ion availability whilst increasing dissolved CO_2. As pH and dissolved inorganic carbon species play critical roles in a number of physiological processes and also influence nutrient availability, changes in these properties will have a fundamental impact upon marine biogeochemistry and ecosystems. This section assesses projected changes in two components of the marine carbonate system, surface ocean pH and the depth of the Aragonite Saturation Horizon (ASH). Outputs of the six models that include carbonate chemistry (see Appendix Table 1) were first evaluated against the present-day carbonate parameters (Bostock et al, 2013), with the projections subsequently based on the best model (GFDL-ESM2G). The mean of all 6 models is also considered for comparison. In addition, pH and ASH projections are generated for all four RCPs to illustrate the impact of different future concentration scenarios.

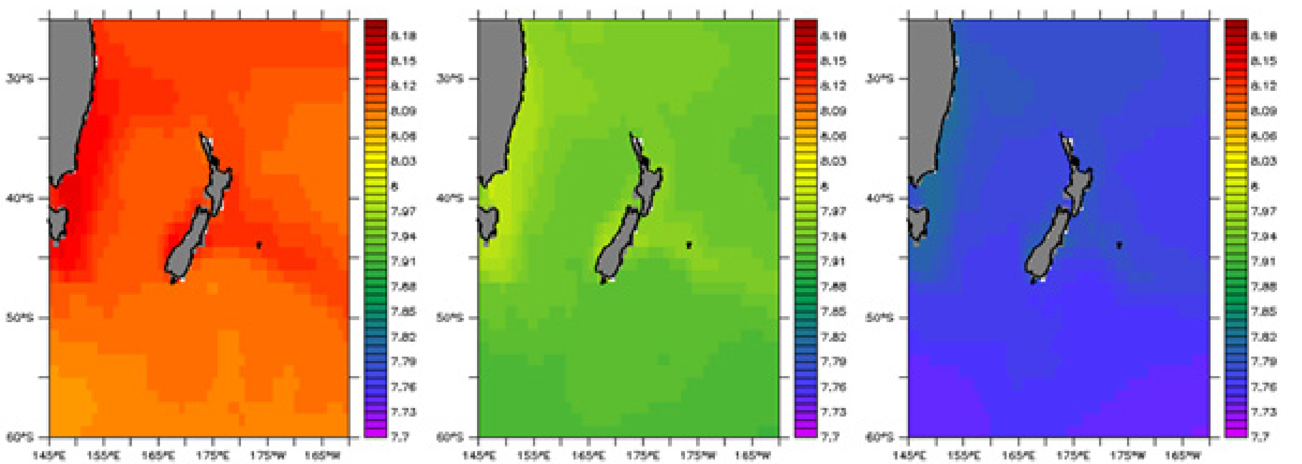


Figure 9. The spatial variation in mean surface pH in the SWP for the present-day (left panel), and projected for Mid-Century (central panel) and End-Century (right panel) using the GFDL-ESM2G model under RCP8.5.

pH

pH is a measure of hydrogen ion concentration and indicates the acidity/alkalinity of a solution. Over recent geological time the pH of the ocean has been relatively stable at ~8.2, but since the late 1870s it has declined to 8.1 in response to anthropogenic CO_2 emissions (Raven et al, 2005). As pH is a negative logarithmic scale, this decline of 0.1 is equivalent to an increase in hydrogen ion concentration of ~30%.

As pH is primarily determined by atmospheric CO_2 and there is no upwelling of low pH water in the SWP, surface pH is relatively uniform. The decline in surface pH at Mid and End-Century is clearly apparent in Figure 9, which shows that the effect of future changes in atmospheric CO_2 concentration on pH override spatial variation arising from natural processes. Minor regional variation is evident, with higher pH in northern Subtropical waters and the East Australian Current, and lower pH in the south. This meridional trend of ~0.03 partially reflects the higher solubility of CO_2, and so lower pH, in colder water. Surface waters in the Subtropical Front on the Chatham Rise have marginally higher pH, due to CO_2 uptake by phytoplankton in this region.

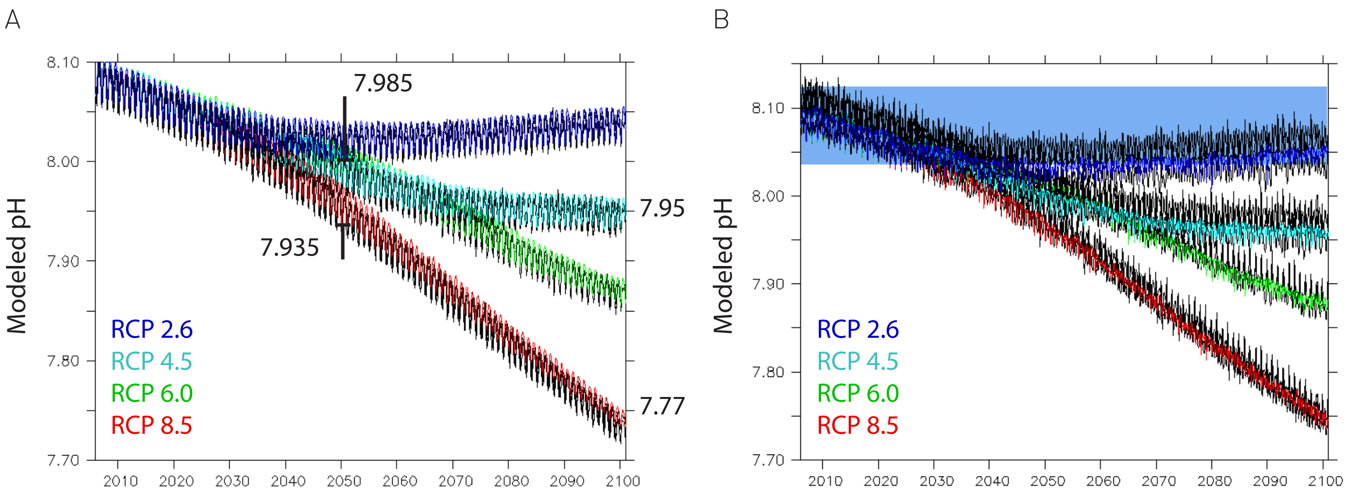


Figure 10. ***A****. Projected surface pH for the EEZ under each RCP, with the Mid and End-Century mean pH identified for RCP4.5 and 8.5. For each RCP the black line indicates the mean of the six models, and the coloured line the best model.* ***B****. shows the same information as* ***A****. for the Chatham Rise region only, with the current pH range (8.04-8.13) indicated by the horizontal blue band. The current pH range was derived from measurements in Subantarctic surface water off the Otago shelf over a 16-year period (1998-2014) on the Munida time series (Bates et al, 2014), at a location on the southern boundary of region 6.*

Figure 10 illustrates how the projected pH differs under different future emission scenarios. The annual sawtooth pattern reflects seasonal variation in pH, with a maximum in summer resulting from phytoplankton uptake of dissolved CO_2, and a minimum in winter when phytoplankton abundance is low. This seasonality results in a relatively large annual pH range of ~0.05, which obscures any difference in the four RCP projections until around 2035. However the pH under the different RCPs subsequently deviates, declining to 7.98 by 2050, and 7.95 by 2100, under RCP4.5 (see Appendix Table 3). Conversely the RCP8.5 scenario shows a steeper decline to 7.94 and 7.77 by 2050 and 2100, respectively. This decline of 0.33 pH units by 2100 is equivalent to an increase in hydrogen ion concentration of 116% since the pre-industrial period. This is consistent with trends in the global ocean, and represents both the lowest pH, and the fastest rate of change in pH, in the last 25 million years (Turley et al, 2006).

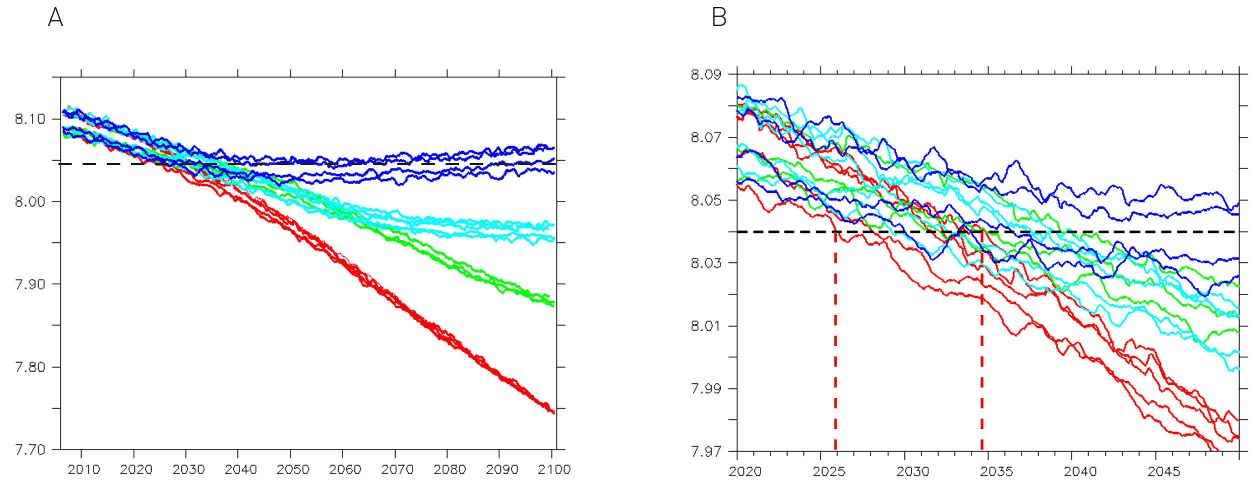


*Figure 11. **A**. Change in annual pH mean (no seasonality) for the Chatham Rise region under all RCPs to 2100, **B**. Projected pH for the period 2020-2050 by the four best models under each RCP, compared with the current measured pH minimum for Subantarctic water (horizontal dashed line). The earliest and latest PoD for RCP8.5 are indicated by the red vertical dashed lines.*

The Chatham Rise region has greater interannual pH variation than the EEZ mean (compare Figs.10A and B), with a higher, but not significantly different pH at 2100, due to in part to higher phytoplankton productivity and so CO_2 uptake in this region (Chiswell et al, 2013). Figures 11A and B show the projected annual mean pH for the four best models for each RCP to 2100, and to 2050, respectively, for the Chatham Rise region. Comparison with the present-day pH minimum further emphasises the sensitivity of surface water pH to future CO_2 concentration. The projected mean pH remains largely within the current pH range under RCP2.6, but falls below the current pH minimum by Mid-Century under all the other RCPs. This "point of departure" (PoD) varies with RCP and model, with the earliest and latest PoD occurring at 2026 and 2034, respectively, under RCP8.5 (see Figure 11B). Conversely the PoD for the Chatham Rise region occurs later under most other scenarios, with a PoD of 2031-2040 under RCP4.5 and 6.0, and no PoD before 2100 for two of the four RCP2.6 models (Figure 11B).

Implications - Research to date suggests that declining surface pH (and associated increases in dissolved CO_2) may cause changes in phytoplankton biodiversity and bacterial processes that will impact marine foodwebs and ocean carbon uptake. In particular, the abundance and distribution of planktonic organisms with carbonate shells, and the foodwebs they contribute to, may be negatively affected by acidification. As pH sensitivity differs between species this makes it difficult to predict when deleterious effects may occur. The PoD, when the annual mean pH falls below the present-day pH range which the ecosystem is assumed to be adapted to, represents a potential threshold which, for the Chatham Rise region and Subantarctic water, is projected to occur between 2026 and 2034.

Aragonite Saturation Horizon (ASH)

A variety of marine organisms, including plankton, corals and molluscs, have carbonate shells or structures produced from dissolved inorganic carbon. An increase in dissolved CO_2 in seawater reduces the carbonate ion saturation, which makes it more challenging to construct and maintain a carbonate shell. Aragonite is the strongest of the types of carbonate used by marine organisms, but also the most soluble, and consequently organisms that use aragonite are more sensitive to ocean acidification. Some of these organisms, such as cold water corals, are further challenged as they live in the deep ocean, where low temperature and high pressure increase the solubility of carbonate. This results in a critical depth, the Aragonite Saturation Horizon (ASH), where solid aragonite begins to dissolve (see Figure 12). The transfer of anthropogenic CO_2 into the deep ocean is causing the ASH to rise towards the surface, with implications for all deep-sea organisms that use aragonite.

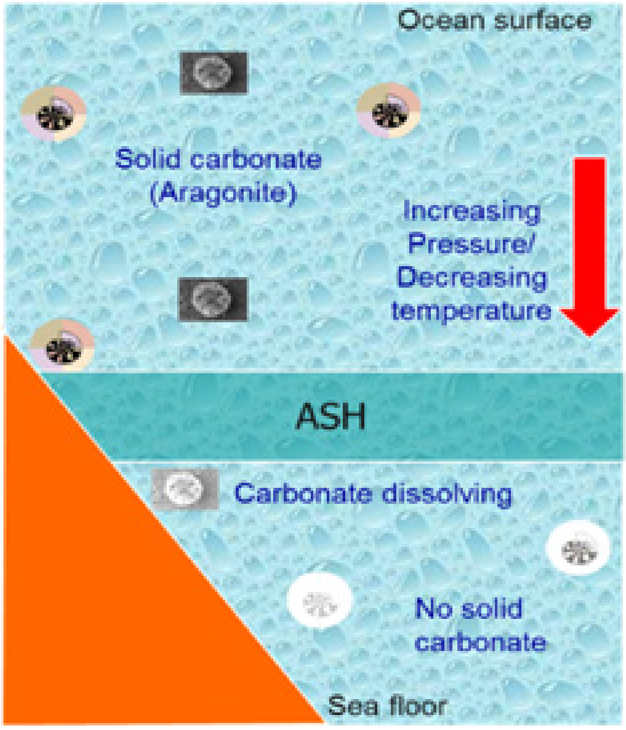


Figure 12. A conceptual figure showing the change in carbonate with depth in the ocean, highlighting the Aragonite Saturation Horizon (ASH), the depth at which solid carbonate in the form of aragonite becomes unstable, and below which it dissolves.

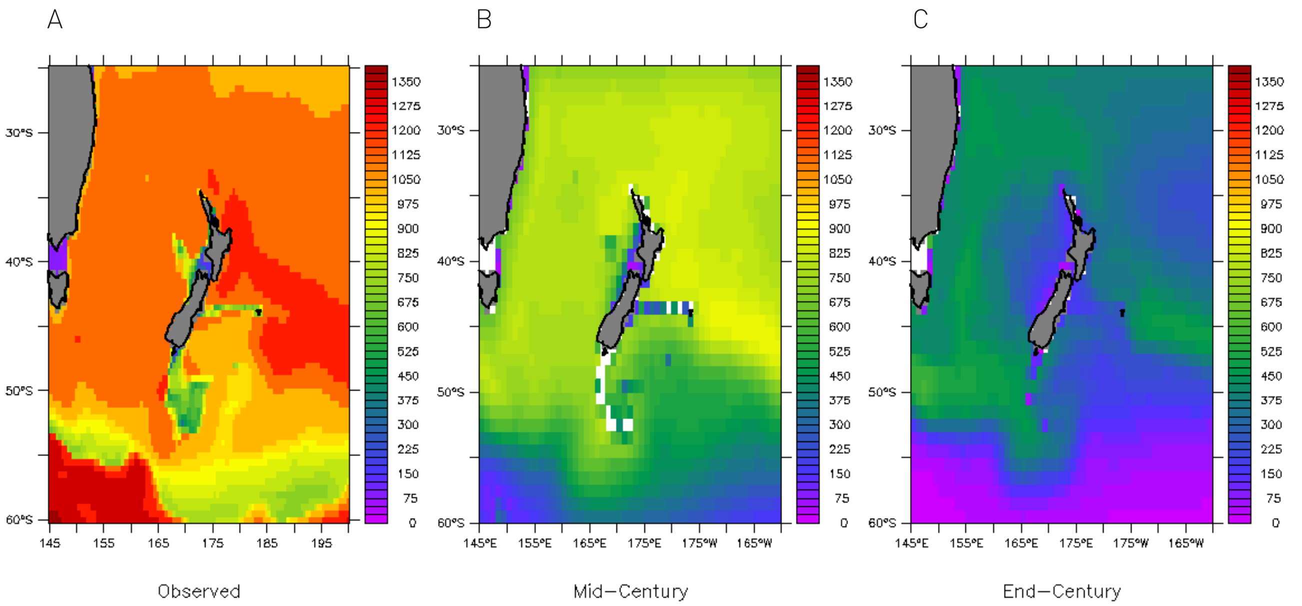


Figure 13. Regional variation in the depth (metres) of the ASH for ***A****. the present-day (Bostock et al, 2015), and projections of future ASH depth for* ***B****. Mid-Century and* ***C****. End-Century, using the GFDL-ESM2G model under RCP8.5.*

Figure 13 shows the present-day variation in ASH depth in NZ waters, being deeper in Subtropical waters, particularly north of the Chatham Rise (~1300m), and shallowest (~900m) in Subantarctic waters south of NZ. This regional variation arises as a result of factors such as differing water temperature and dissolved inorganic carbon content. The impact of increased anthropogenic CO_2 entering the ocean is apparent in Figures 13B and C, with the ASH shoaling to 820-950m across much of the EEZ by mid-Century. The shoaling in the colder Subantarctic water is particularly evident, with a projected ASH depth of ~350-400m by Mid-Century and ~100-200m by End-Century. In polar waters south of 52°S the ASH shoals to the surface by End-Century, consistent with projections that 70% of the Southern Ocean will be undersaturated with respect to aragonite by 2100 (Hauri et al, 2015).

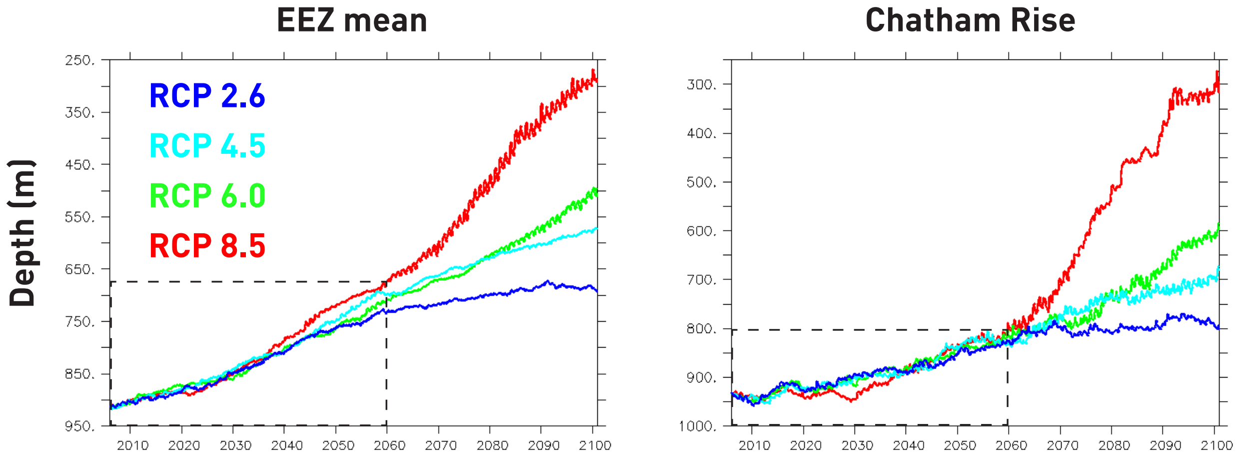


Figure 14. The projected change in mean ASH depth to 2100 for the EEZ (left panel), and the Chatham Rise region (right panel), under the four RCPs (see legend). The dashed line in both figures indicates the projected ASH depth at 2060 under RCP8.5.

The temporal trend in the ASH depth shows no significant difference for the SWP under the different RCPs until 2040 (see Figure 14A), and until 2060 for the Chatham Rise region (see Figure 14B). This slower trend in the change in ASH depth, relative to the surface pH trend (Figure 10), reflects the temporal delay in transfer of CO_2 from surface to deep water. Regional differences in shoaling are apparent, with the Chatham Rise ASH being 125m deeper than the mean ASH for the EEZ in 2060 under RCP8.5. However, the steeper post-2060 shoaling in the Chatham rise region results in a similar ASH depth by End-Century.

Implications – These results suggest that, at least until Mid-Century, deep water organisms that use aragonite have a greater chance of survival, and potentially adaptation, in the Chatham Rise region. Consequently, the Chatham Rise region may represent a refuge for deep water biota that use aragonite, which should be considered for protected groups such as Cold Water Corals (see below) and in the location of Marine Protected Areas. Furthermore, the projected shallowing of the ASH indicates that by 2100 the distribution of deep-water organisms that utilise carbonate will be spatially restricted throughout the SWP and particularly in Subantarctic and polar waters to the south. Shoaling of the ASH to the surface in these colder Subantarctic waters by End-century suggests that planktonic groups, such as the pteropods, will be unable to maintain their aragonite structures, with implications for foodwebs.

Dissolved Oxygen

Warming reduces dissolved oxygen by lowering the solubility of oxygen, increasing removal via respiration, and reducing its transfer into the deep ocean via declining circulation. As a result some oceanic regions, that already support midwater low-oxygen zones are expected to become more hypoxic, which may restrict the abundance of pelagic and mesopelagic organisms, including fish. The EEZ does not currently contain low-oxygen waters, with lowest concentrations of 0.12 mmol m^{-3} in the mid-water column north of NZ. Figure 5 in the Appendix shows the projected change in dissolved oxygen along a meridional transect east of New Zealand on 180°E. There is no evidence of a significant decline in dissolved oxygen, with the largest change a decrease of <3% in deep water (>4000m) south of NZ by End-Century. However, the present-day data simulations have not been validated against dissolved oxygen measurements for the SWP and so these projections should be treated with caution.

Biological variables

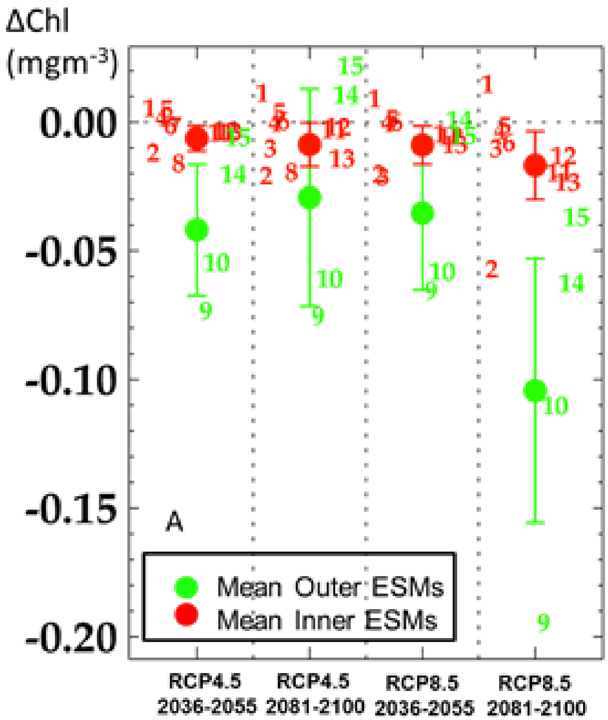
Surface Chlorophyll-a and Integrated Primary Production (IntPP)

Chlorophyll-a is an indicator of phytoplankton biomass in surface waters and a proxy for primary productivity. Phytoplankton biomass and distribution is influenced by a number of factors that may be altered by climate change, including SST, mixing, surface layer depth and stratification (all of which influence light and nutrient availability), dissolved inorganic carbon and pH, as well as indirect factors such as grazing and competition for resources. Current models incorporate some, but not all of these factors. Chlorophyll-a is well constrained by satellite remote sensing in the surface ocean around NZ, and so was used to assess the best (Inner) model ensemble (see Appendix Figure 3).

Projections of chlorophyll-a for the SWP show no significant change under RCP4.5 by 2100, whereas there is a significant decline, by 0.043 mg Chl m^{-3} (21% of present-day mean concentration) by End-Century under RCP8.5 (for all models, see Figure 15A). Whereas the Inner ensemble show good agreement, the Outer ensemble show considerable spread, with certain models (9, 10 and 14) indicating greater decreases by End-Century. Regional variation in projected change is apparent under RCP8.5 by End-Century, with Subtropical water in the northern half of the EEZ showing a slight decline and Subantarctic water in the south showing no significant change (hatched areas in Figure 15B). There are minor increases (<0.04 Chl-a mg m^{-3}) in the central Tasman Sea in region 2 that may result from increased mixing and elevated iron supply (See Figure 8D), and also in Subantarctic water associated with surface layer shallowing and increased nutrient availability (see Figures 4 and 8A-C). Conversely, decreases in chlorophyll-a are associated with the southward extension of the East Australian Current along south-east Australia, and also immediately south of the South Island.

Phytoplankton form the base of marine foodwebs and support ecosystems and fisheries. Their distribution is reflected in surface chlorophyll-a, and also the net rate of phytoplankton production ("IntPP"), measured as the amount of carbon produced per m^2 per day integrated over the whole water column. The projected change in chlorophyll-a and IntPP generally show similar trends (see Figure 16A), with a meridional pattern of declining IntPP in northern Subtropical waters, which is significant at 20-25°S north of NZ, and no significant change in IntPP in Subantarctic waters by End-Century under RCP8.5 (see stippled region in Figure 16B). The regional variation in projected IntPP for Mid- and End-Century under RCP4.5 and 8.5 is compared for each sub-region in Appendix Figure 6.

A



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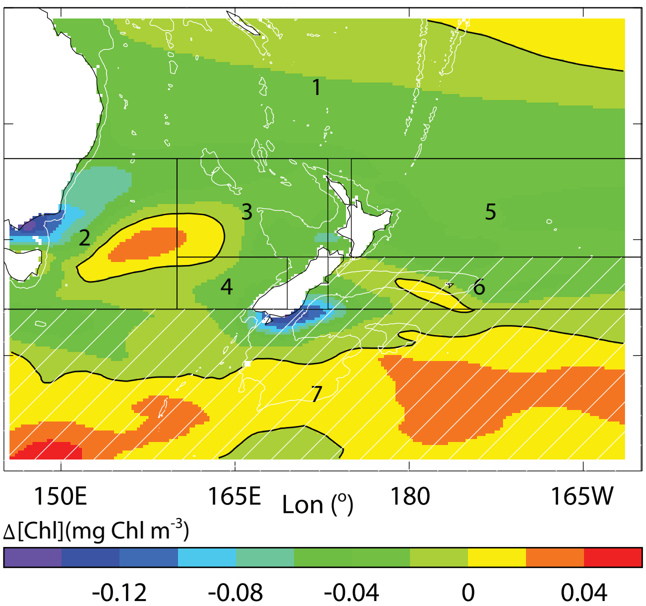

*Figure 15. **A**. Inner (red) and Outer (green) ensemble projections of change (Δ) in mean surface chlorophyll-a (mg Chl-a m^{-3}). Vertical dashed lines separate the different projections for Mid- and End-Century under RCP4.5 and 8.5. Negative values indicate a decrease in concentrations and the horizontal dashed line indicates zero change. **B**. shows the regional variation in projected changes in chlorophyll-a, based upon the Inner ensemble mean under RCP8.5 by End-Century (Rickard et al, 2016).*

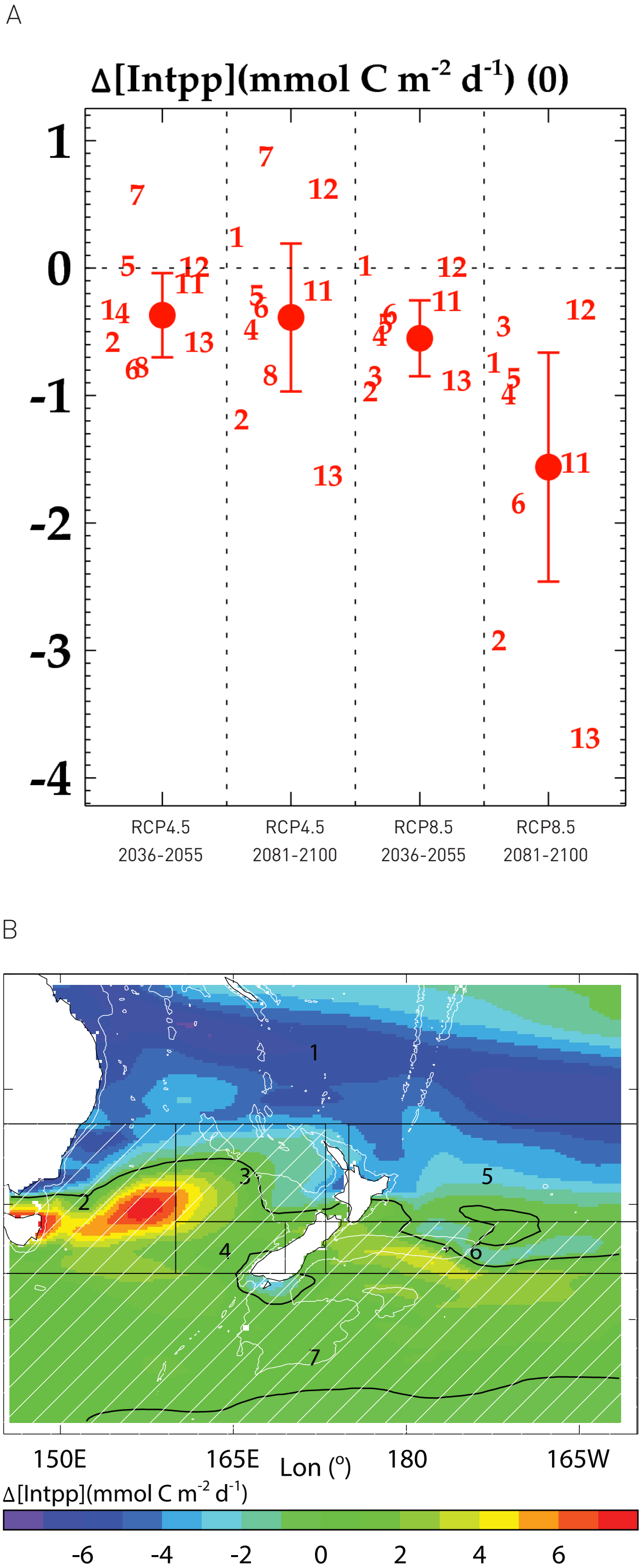

*Figure 16. **A**. Inner ensemble projections of change (Δ) in mean surface IntPP for the RCP4.5 and 8.5 scenarios at Mid- and End-Century for the SWP (separated by vertical dashed lines). Negative values indicate a decrease in rate, and the horizontal dashed line indicates zero change. **B**. Spatial variation in projected IntPP based upon the Inner ensemble mean under RCP8.5 for End-Century. Black contours indicate zero change, and white contours the 1000 metre isobath. Stippled sub-regions are not considered to represent significant changes (see Appendix and Rickard et al, 2016).*

Implications – Projections indicate an overall reduction in global marine IntPP of 2–13% (Bopp et al., 2013), although there are major knowledge gaps regarding the drivers of primary production and their interaction, which introduces uncertainty in these projections. IntPP shows no significant decline in the SWP by End Century under RCP4.5, but a significant decrease, of 2.1 mmol C m^{-2} d^{-1} (6% of present day mean concentration), under RCP8.5. This decrease in IntPP may translate to a decline in ecosystem productivity and carbon export (see below), although this will be regionally variable with the warmer Subtropical waters, which are already characterised by low primary production and biomass, experiencing the most significant decline.

Particle flux

A proportion of the organic matter produced by phytoplankton in the surface of the ocean sinks down through the water column. This particle flux from surface to sea-bed is an important factor that determines energy flow through marine ecosystems, and also the amount of carbon sequestered in the deep ocean. Determining the impact of climate change on particle flux into the ocean interior is important for predicting future carbon uptake by the ocean, and future change in marine ecosystems and fish stocks. Changes in particle flux in response to climate change were assessed using methodology described in the Appendix, and applying 12 of the Earth System models (see Appendix Table 4) to generate four flux products:

- *fluxRelease*: the total particle flux that sinks out of the surface layer, which is a measure of the total particulate organic material available to organisms living in the water column;
- *fluxSeabed*: the total particle flux that reaches the seabed, and is available as food for benthic organisms;
- E-ratio (the Export ratio): the proportion of particle flux from the surface ocean that is consumed and transferred into marine food-webs; and
- Flux attenuation: the fractional reduction in particle flux between the surface and the sea-bed.

The present-day *fluxRelease* is generally higher in Subtropical waters and lower in Subantarctic waters in the SWP (Figure 17A), although there is greater interannual variability in the Subtropical front, east and west of NZ. Present-day detrital flux at the seabed, *fluxSeabed*, is higher in shallower waters, and also in areas of elevated primary production including continental shelf waters, the Chatham Rise, Campbell and Challenger Plateaus (Figure 17B). Comparison of Figs 17A and B confirms that the flux at the seafloor is significantly lower in deeper waters, as expected.

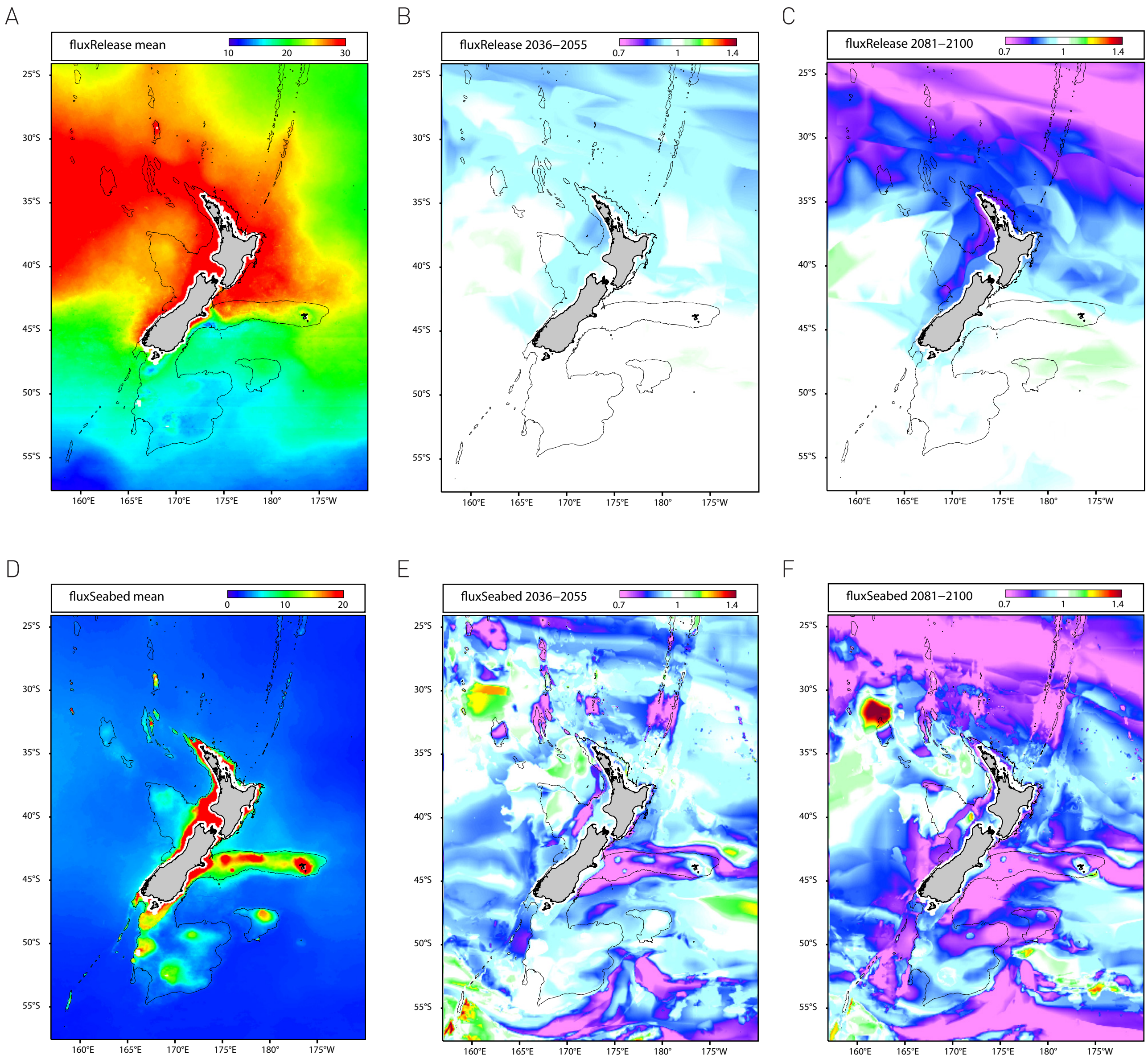

Figure 17. ***A****. Present-day mean flux at the base of the surface mixed layer (fluxRelease, mg C m^{-2} d^{-1}), and projected changes in fluxRelease for* ***B****. Mid-Century and* ***C****. End-Century under RCP8.5. The 1000m isobath is shown by the dashed line.* ***D****. Present day mean flux at the Seabed (fluxSeabed, mg C m^{-2} d^{-1}), and projected changes in fluxSeabed for* ***E****. Mid-Century and* ***F****. End-Century under RCP8.5. Warm colours indicate an increase and cool colours a decrease in flux, with white indicating no change.*

Overall the projections indicate a consistent decrease in both *fluxRelease* and *fluxSeabed* over time. Projected declines are greater at End-Century relative to Mid-Century (compare Figures 17B with C, and E with F), under RCP8.5 relative to RCP4.5 (data not shown), and for *fluxSeabed* relative to *fluxRelease* (compare Figure 17B with E, and C with F). Projected decreases in *fluxRelease* are larger for northern Subtropical waters than for Subantarctic waters (see Figures 17B and C). The E-ratio was projected to decline everywhere in the NZ region (see Appendix Figure 7), and Flux attenuation with depth increases in most areas, especially over shallower waters, meaning less organic material is available at a given depth (see Appendix Figure 8).The decreases in *fluxRelease* are predominantly driven by projected decreases in IntPP (see Figure 16B), as changes in the E-ratio are predicted to be small. Changes in *fluxSeabed* are predicted to be greater than changes in *fluxRelease*, in response to substantial future increases in flux attenuation with depth, particularly over the shallower waters of the Chatham Rise and Campbell Plateau. The regional variation in changes in *fluxRelease* and *fluxSeabed* are presented in Appendix Table 5. For the NZ region, the median decreases at End-Century under RCP8.5 are 9.1% (*fluxRelease*) and 12.5% (*fluxSeabed*), both of which are outside the range of present day interannual variability. Under RCP4.5, the median decreases at the end of the Century are 4.1% (*fluxRelease*) and 7.5% (*fluxSeabed*).

Implications – Decreases in vertical particle flux suggests impacts on pelagic and benthic foodwebs and potential future declines in the food available to fish (see below). The EEZ is an important sink for CO_2 (McDiarmid et al, 2013), exceeding that of NZ forests, and the projected decrease in vertical particle flux would lower carbon sequestration in the deep ocean around NZ.

Impact of changing particle flux on fish species

Recent global models suggest that fisheries stock sizes may increase towards the poles as higher growth rates accompany increasing temperatures in these regions (Cheung et al, 2010). However, current understanding of the factors that determine mortality, growth (stock productivity) and recruitment, and the sensitivity of these factors to climate change, is insufficient to generate robust future projections for fisheries. This is a challenge for Marine Stewardship Council certified fisheries, as they are required to account for climate change in their management plans[1].

A preliminary indication of the impact of climate change on future fisheries yield was developed based upon changes in food supply. Particle flux from the surface ocean ultimately provides the food for fish, and a positive relationship between particle flux and fishery yield has been identified over broad spatial and temporal scales (Friedland et al, 2012). In NZ waters, commercially-important fish tend to feed predominantly on other fish, with an often substantial contribution in their diet of prawns, shrimps and other invertebrates near the sea-bed, and pelagic invertebrates such as squid, krill and salps (Dunn et al, 2009). These prey species are dependent on sinking material for their food, and so any change in sinking particles will affect prey abundance and productivity, and so potentially influence fishery yield. Consequently, a "fish-based" flux (fluxFish) can be generated, where the particle flux is combined with the current spatial distribution of fish species and their diets, to generate projections of future changes to food supply and maps of where changes to particle flux (and hence prey availability) may be greatest (see Methodology in Appendix).

The projected changes in the flux food supply are shown by region and depth range in Appendix Table 5, with the most significant projected changes at depths greater than 1500m in Subtropical waters, and at the End-Century under RCP8.5. The projected changes in fluxFish depend on changes in primary productivity, E-ratio and flux attenuation in the areas that a species live; consequently, changes to fluxFish at the species level depend more on where the fish are found than whether they feed in benthic or pelagic modes (data not shown). For all 38 species fluxFish is projected to decrease, with a range of -2.2 to -24.6% (see Appendix Table 6), again with largest declines at the End-Century under RCP8.5. There is some variability in the change projected by the 12 models, as shown for tarakihi, for which one model indicates an increase relative to the present-day range whereas the majority indicate a decline by End-Century. Conversely, most models indicate no significant change in fluxFish from the present day range for orange roughy (see Figure 18).

[1]https://www.msc.org/healthy-oceans/the-oceans-today/climate-change

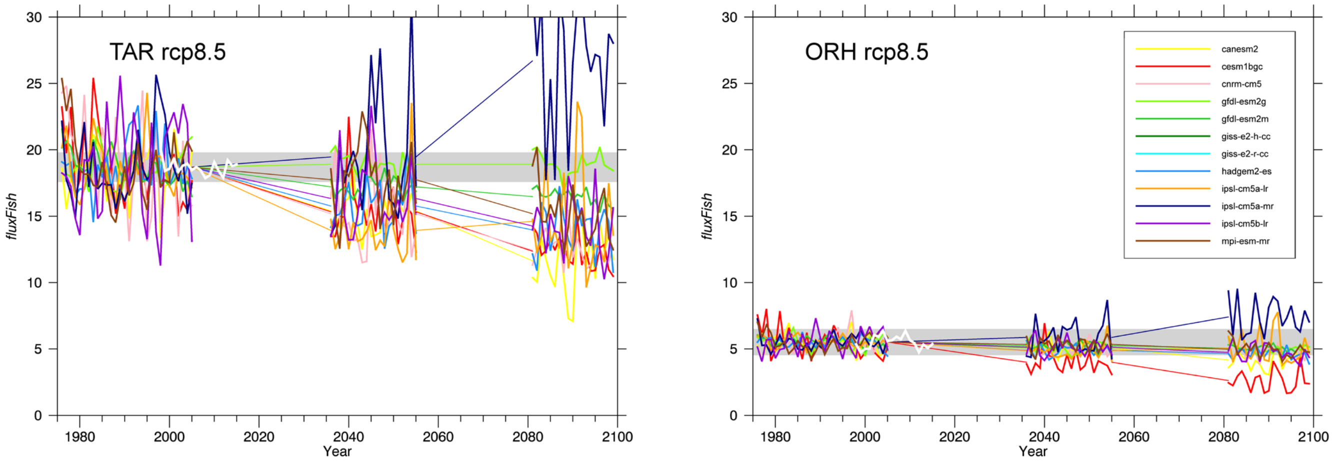

*Figure 18. fluxFish estimated for each of the 12 models (see colour key in legend) for tarakihi (left panel) and **B**. Orange roughy (right panel) under RCP8.5 scenario from 1975 projected to 2100. The range (± 2 standard deviations) in the present-day estimates is indicated by the grey bands, and deviation outside this band is considered a significant change.*

Implications – The fish species potentially most affected by projected changes in particle flux, as a result of climate change in NZ waters, are the northern spiny dogfish, gemfish, frostfish and tarakihi, whereas species least affected are the black oreo, barracouta, southern blue whiting and blue warehou (see Appendix Table 6). Regional variation is also apparent, with a decline in *fluxFish* being greater in some regions than others. For example, the largest projected declines for orange roughy occur on the Challenger Plateau, for tarakihi, hake and ling on the Chatham Rise, and for bluenose on the NW shelf (see Appendix Figure 10). The projected reductions in food supply for fish stocks included in the NZ Quota Management System may reduce fish condition, affect recruitment, lower fisheries productivity and potential fishery yields. Decreases in food availability may also lead to changes in the spatial distributions of fish stocks, which could affect patterns of fishing effort and interactions between fish stocks, and may require changes to survey strata and adjustment to the relative catch limits between Quota Management Areas (QMAs).

Cold Water Corals

Cold water corals provide reefs and complex habitat for deep sea invertebrates and juvenile fish. NZ waters are a global hotspot for cold water corals, due to the high biodiversity and extensive spatial coverage (Tittensor et al, 2010), and is recognised by their protected status. Many cold water corals have an exoskeleton composed of aragonite, and so are sensitive to the depth of the ASH (see above); however they may also be influenced by climate change via warming of deep water and changes in food supply. By incorporating the future conditions projected by the models into habitat suitability models derived from the current distribution of cold water corals and associated environmental variables, the potential future change in suitable habitat, and so inferred future distribution, was examined for different cold water coral groups, as detailed in the Appendix and in Anderson et al (2016).

Cold water coral habitat suitability was predicted to decline over much of the NZ region by End-Century, the exception being the Chatham Rise where, for most groups, suitable habitat remains either stable or increases. Habitat suitability for scleractinian corals was projected to decline markedly over much of the NZ EEZ by the End-Century (see Figure 19), particularly around the Campbell and Bounty plateaux, and the Challenger Plateau and Lord Howe Rise in the north-east Tasman Sea. Notable declines in habitat suitability were also apparent for three of the four individual scleractinian species, although this was variable (data not shown). Some bamboo and gorgonian coral species, and the black corals, are less affected by projected changes in environmental conditions (data not shown; see Anderson et al, 2016).

[1]https://www.msc.org/healthy-oceans/the-oceans-today/climate-change

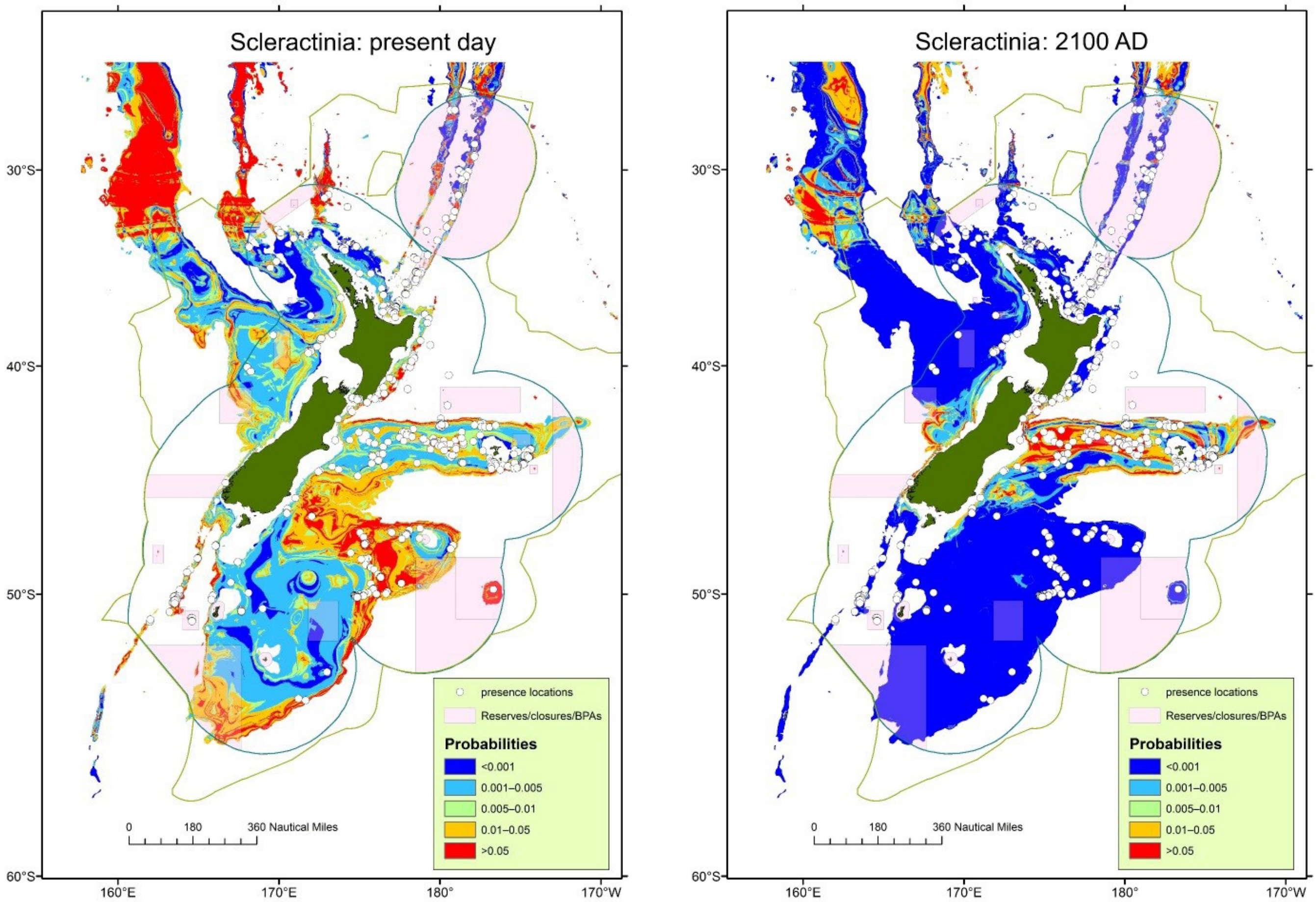

Figure 19. Estimated probability of occurrence of suitable habitat for four scleractinian coral species for the present-day (left panel) and End-Century (right panel) under RCP8.5.

Implications – The loss of scleractinian corals, and other cold water coral species that provide complex habitat, from deep waters around NZ will likely have negative impacts on biodiversity and productivity of deep-sea ecosystems by the End-Century. For some areas of the Chatham Rise suitable habitat for scleractinian reef-forming species is projected to remain unchanged or increase, suggesting that this region could be considered as a future location for marine protected areas. This strategy would increase the time period for cold water corals to adapt to climate change, and enhance their prospects of survival.

CONCLUSIONS

- Projections show that most of the ocean properties assessed are highly sensitive to future CO_2 concentration emissions, with the high emission scenario (RCP8.5) yielding the most significant projected changes.
- Mean sea surface temperature will increase by 2.5ºC, and exceed 3ºC in the north Tasman Sea, by 2100. Decreases in surface chlorophyll-a, nitrate, phosphate and pH will have occurred by 2100, accompanied by shallowing of the surface layer.
- Changes in significant wave height will be relatively minor by 2100, with the largest increases (<+4%) in Subantarctic waters south of NZ, and decreases (-5%) on the Chatham Rise.
- Surface water nutrient concentrations will decline, particularly in the eastern Chatham Rise region, with a decrease in nitrate by ~9% under RCP8.5 by 2100. Conversely dissolved iron is projected to increase in Subtropical water.
- Surface pH will decline by 0.33 under RCP8.5 by 2100, with the resulting pH (7.77), and the rate of change in pH, being unprecedented in the last 25 million years. Subantarctic surface pH will fall below the current pH minimum around 2030, with acidification creating corrosive conditions for organisms with carbonate shells in Subantarctic waters.
- Integrated Primary Production will decline by 6% from the present day under RCP8.5 by 2100, with Subtropical waters, which are already characterised by low primary production, experiencing the largest decline.
- The decrease in particle flux from the surface to the seabed, of 9-12% by 2100, indicates that carbon sequestration will decline in the open ocean around New Zealand.
- Changes in particle flux will alter the food available for fish. A decline in particle flux was identified for all 38 species assessed (including 30 commercial species), ranging from 2.2 to 24.6%, by 2100. The largest decline in particle flux occurs in areas occupied by the northern spiny dogfish, gemfish, frostfish and tarakihi, and lowest decline in areas occupied by black oreo, barracouta, southern blue whiting and blue warehou.
- Climate change will not significantly lower dissolved oxygen in the mid-water around NZ, but the depth at which carbonate dissolves will be significantly more shallow. This will contribute to a decline in suitable habitat for cold water corals in New Zealand waters, and impact deep-sea ecosystems and biodiversity. The Chatham Rise may provide temporary refugia, which should be considered in spatial management of marine protected areas.
- The regional variation of the impact of climatic change in New Zealand waters needs to be considered in management and policy decisions. For example, regions projected to be most sensitive to climate change include Subantarctic waters south of 50ºS and the eastern Chatham Rise, which support important fisheries, and Subtropical waters north-east of NZ.

Table 1. Summary table of present-day and projected mean values (Δ = absolute change; % Δ = % change) for the middle and end of the 21st Century for all variables under RCP4.5 and 8.5 for the South West Pacific. As pH is the negative logarithm of hydrogen ion concentration, % Δ for pH indicates the percentage change in hydrogen ion concentration (shown in italics).

		Present day	RCP4.5 Mid century			RCP4.5 End century			RCP8.5 Mid century			RCP8.5 End century		
	Unit	Mean	Mean	Δ	% Δ	Mean	Δ	% Δ	Mean	Δ	% Δ	Mean	Δ	% Δ
SST	oC	15.84	16.6	0.8	5.1	17.0	1.2	7.6	16.84	1	6.3	18.3	2.5	15.8
MLD	m	91	87.0	-4	-4.4	84.0	-7	-7.7	85.0	-6	-6.6	76.0	-15	-16.5
Wave Height	m	2.79	2.8	0.01	0.5	2.8	0	-0.1	2.8	0.01	0.4	2.8	0.03	1.1
Nitrate	mmol/m3	5.31	5.1	-0.2	-3.8	5.1	-0.25	-4.7	4.96	-0.35	-6.6	4.82	-0.49	-9.2
Phosphate	mmol/m3	0.5	0.5	-0.005	-1.0	0.5	-0.01	-2.0	0.47	-0.03	-6.0	0.46	-0.04	-8.0
Silicate	mmol/m3	3.2	3.3	0.1	3.1	2.9	-0.3	-9.4	3.2	0	0.0	3.02	-0.18	-5.6
Fe	mmol/m3	0.13	0.1	0.01	7.7	0.1	0.01	7.7	0.15	0.02	15.4	0.16	0.03	23.8
pH		8.11	7.99	-0.12	32.1	7.95	-0.15	42.2	7.93	-0.17	48.3	7.77	-0.33	116.3
ASH depth	m	951	717	-215	30.0	598	-340	56.9	692	-240	34.7	337	-595	176.6
Chl-a	mg/m3	0.2	0.2	-0.01	-5.0	0.2	-0.01	-5.0	0.195	-0.005	-2.5	0.157	-0.043	-21.5
NPP	mmol C /m2/d	33.52	33.0	-0.5	-1.5	32.9	-0.6	-1.8	33.22	-0.3	-0.9	32.02	-1.5	-4.5

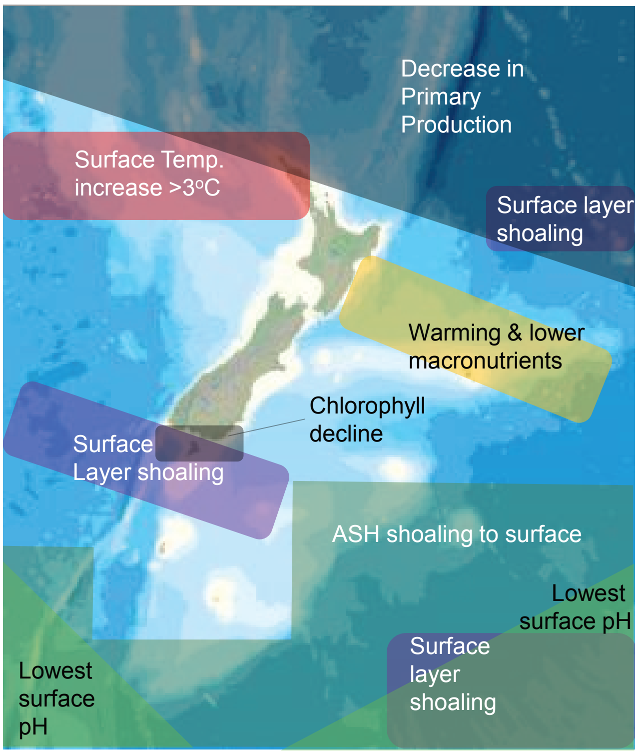

Figure 20. Regional extremes for climate-sensitive variables in the surface ocean around New Zealand projected for 2080-2100.

NEXT STEPS AND RECOMMENDATIONS

These future projections provide a valuable window into how the open ocean around New Zealand may alter over the following century in response to climate change. To strengthen confidence in the projected outcomes and implications, and enable robust future management of our oceans, the following steps are recommended:

- The projections are currently limited by the low spatial resolution of global models, which is relatively coarse compared to the scale at which biological and ecosystem processes occur. Development of high-resolution regional NZ models for downscaling global model projections to regional and coastal scales is required.
- Increased data collection to underpin and validate the regional NZ models
- The key processes that link climate change to marine ecosystem structures need to be identified. Current understanding is largely based on studies using single variables, whereas there is a need to assess interactive effects of more than one variable.
- Targeted research in regions that are vulnerable to climate change, as identified by the projections, particularly those of ecological importance and socio-economic value such as the Chatham Rise.

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APPENDIX

Future concentration scenarios

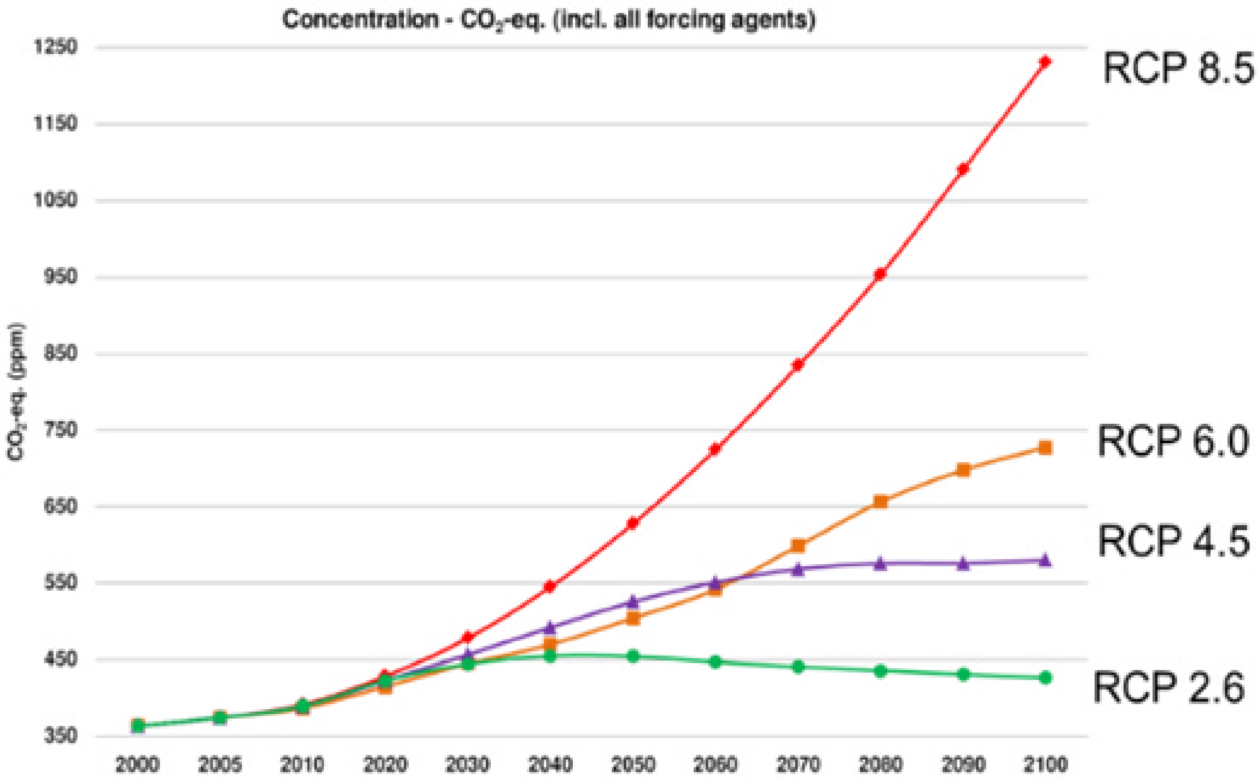

Figure 1. Atmospheric CO_2-equivalent concentrations (in parts-per-million-by-volume) under the four Relative Concentration Pathways (RCPs) (van Vuuren et al, 2011).

Earth System Model validation for the NZ region

Although imperfect, and of relatively coarse spatial resolution (~1°× 1° latitude), Earth System Models currently represent the best options for future projection of marine physical and biogeochemical processes in the NZ region. The Coupled Model Intercomparison Project 5 (CMIP5) is an international project that stores output from a number of these models; 16 of which include marine biogeochemical cycling, and 6 of which include the carbonate system. Some of these models rely on the same biogeochemical model, but use different hydrodynamic models, and so the 16 models used in this study are derived from 10 model centres (see Table 1; Rickard et al, 2016).

An assessment was carried out to determine how robust the outputs of each model were for the SWP region, to identify the best suite of models for climate change projections. The performance of each model was assessed by comparing model output for the present-day period, with current observations for particular variables. As biogeochemical data are both sparse and unevenly distributed in the SWP, only certain variables were considered suitable for validation purposes: chlorophyll-a, Sea Surface temperature, nutrients, mixed layer depth (see Figure 2). Present day model performance was assessed using two metrics - the Root Mean Square Error (RMSE) & the Bias – to determine the difference between the observational data and present day simulation. The models were then ranked based upon their score derived from the RMSE and the Bias, and divided into two ensembles. The "Inner" ensemble is the models with the best overall rankings across all variables, and the "Outer" ensemble the lower overall ranking. The rationale here is that the Inner models, which best describe present-day conditions, are most likely to best describe future changes. A full assessment of the ability of the CMIP5 models to represent future conditions in the SWP Ocean is presented in Rickard et al (2016).

Table 1. Number, name and biogeochemical model component for the 16 models that include marine biogeochemical cycling in CMIP5. The six shaded models include carbonate system parameters (Rickard et al, 2016).

Model Number	Model	BGC Model
1	CANESM2	CMOC
2	CESM1BGC	BEC
3	CMCC-CESM	PELAGOS
4	CNRM-CM5	PISCES
5	GFDL-ESM2G	TOPAZ2
6	GFDL-ESM2M	TOPAZ2
7	GISS-E2-H-CC	NOBM
8	GISS-E2-R-CC	NOBM
9	HadGEM2-CC	Diat-HadOCC
10	HadGEM2-ES	Diat-HadOCC
11	IPSL-CM5A-LR	PISCES
12	IPSL-CM5A-MR	PISCES
13	IPSL-CM5B-LR	PISCES
14	MPI-ESM-LR	HAMOCC5.2
15	MPI-ESM-MR	HAMOCC5.2
16	MRI-ESM1	MRI.COM3+NPZD

The importance of this validation approach is shown for chlorophyll-a (the photosynthetic pigment, which is an indicator of phytoplankton biomass) in Figure 3, which shows present-day surface chlorophyll-a data obtained from satellite ocean colour data (Figure 3A). The output from the Outer Ensemble models (Figure 3C) gives a poor representation of the present-day data, with generally elevated chlorophyll-a in SubAntarctic waters and across the Chatham Rise, with the Subtropical contours displaced to the north (compare Figure 3A and 3B). The use of the Inner ensemble of best models gives a more realistic, though not perfect representation, as shown in Figure 3B. Temporal agreement of the Inner ensemble was also confirmed by comparison of mean monthly projected present-day values with observed chlorophyll-a (Rickard et al, 2016). Consequently the Inner ensemble was used to generate projections for most other variables, including those for which observational datasets were not available (except for pH and aragonite saturation horizon; see below).

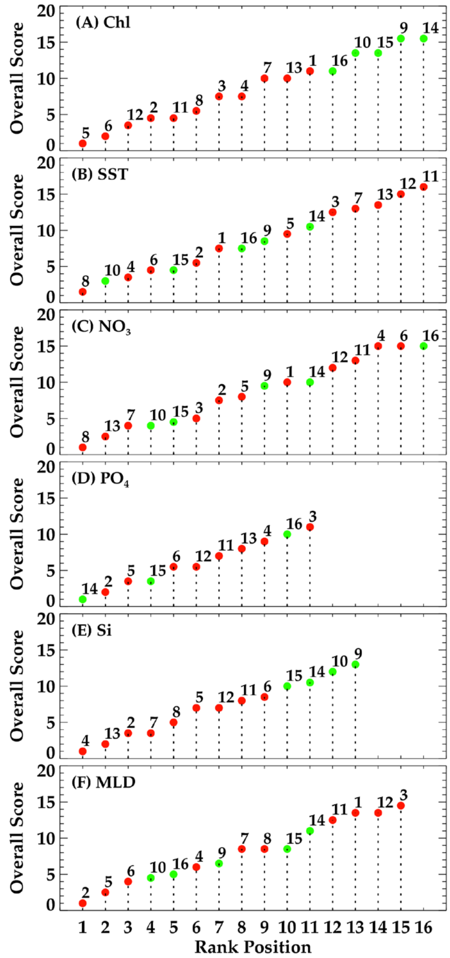

Figure 2. The rank position of each model (identified by number from Table 1), with the lowest number on the x-axis indicating the best performing model, for the following variables: A) chlorophyll-a B) Sea Surface Temperature C) nitrate D) phosphate E) silicate F) and G) Surface Layer Depth (MLD). Compilation of ranking for different variables identified the "Inner" ensemble, the seven best models (red dots), and the remaining less accurate models, the "Outer" ensemble (green dots). Identification as an Inner or Outer model only reflects the suitability for the SWP. Adapted from Rickard et al (2016).

Significance – A significant change in a variable is where the magnitude of multi-model mean change is greater than the inter-model standard deviation, and greater than 80% of models agree on the sign of the mean change for the variable.

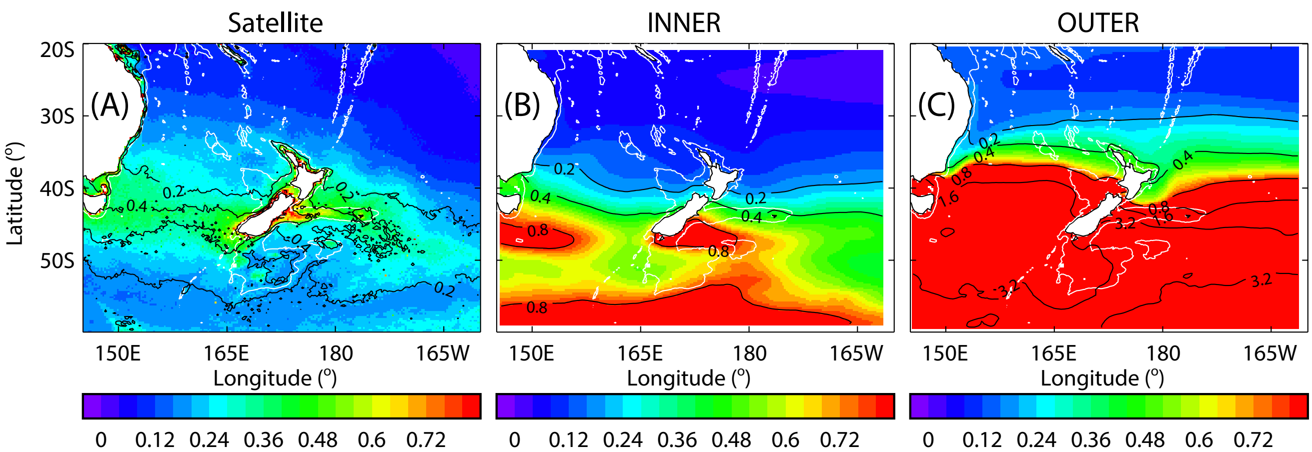

*Figure 3. **A** Mean observed chlorophyll-a (SeaWiFS data 1998-2010 (http://podaac.nasa.gov; Chiswell et al, 2013), and NASA Ocean Color website (http://oceandata.sci.gsfc.nasa.gov/) from 8-day 9-km satellite composites. **B** Mean output for the Inner model ensemble, and **C.** mean output for chlorophyll-a for the Outer model ensemble.*

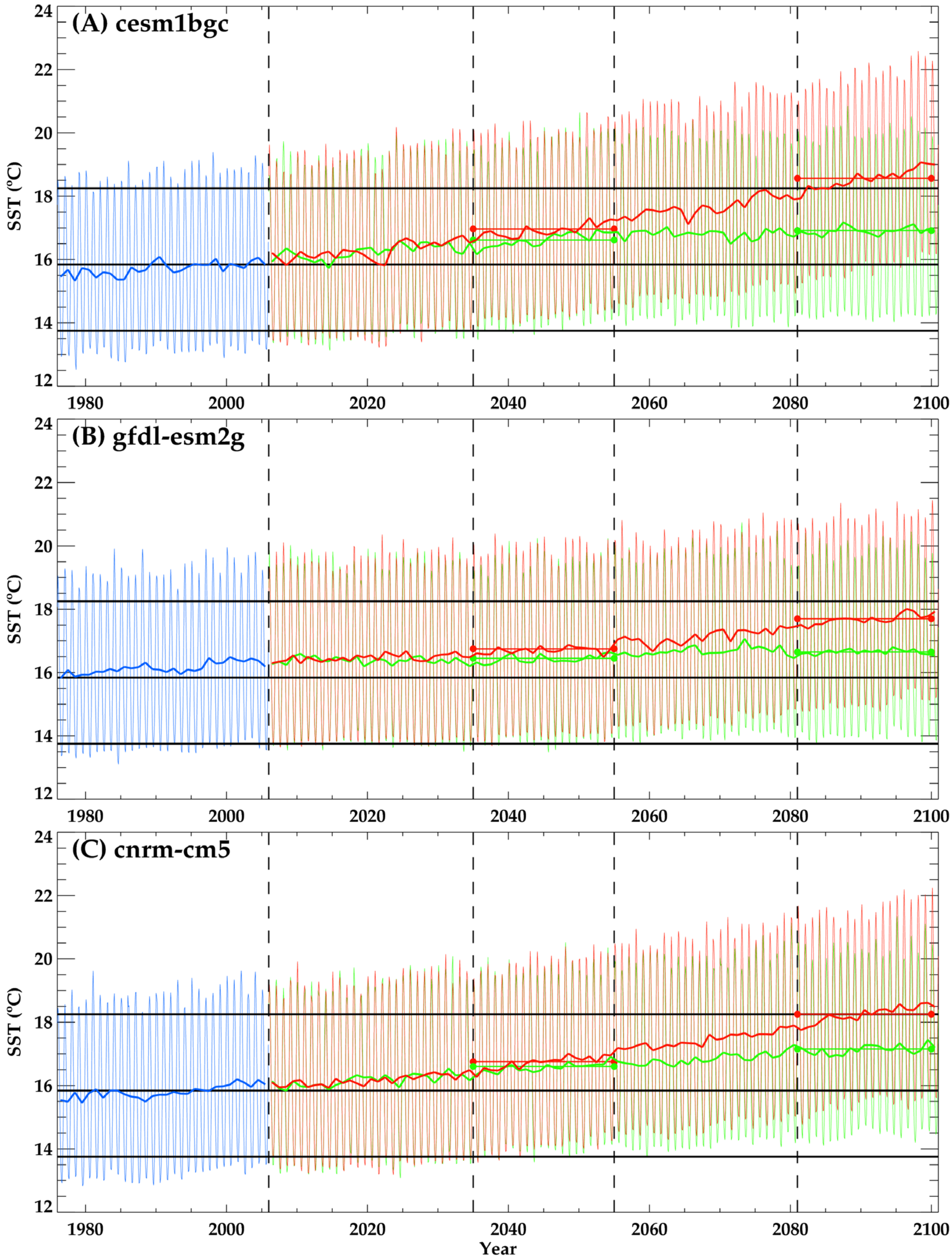

Figure 4. Projected changes in mean SST under RCP4.5 (green) and 8.5 (red), compared with SST for the present-day period (blue), using three different Inner ensemble models in A)-C). The vertical dashed lines delineate the three observation periods (present-day, Mid- and End-Century), with the present-day mean SST and range from observational data (World Ocean Atlas) indicated by the horizontal black lines. The short horizontal lines in the 2035-2055 and 2081-2100 periods indicate the mean projected SST for RCP4.5 (green) and 8.5 (red) for the Mid- and End-Century.

Significant wave height

Projections of future wave climate were generated using a different approach. Wave simulations were obtained using the Wavewatch III model (Tolman, 1991; 2009), with a present day simulation (1970-2000) generated on a global (1.125° × 1.125° resolution), and also a NZ regional (0.125° × 0.09375°) grid. These were compared with four future scenarios from IPCC AR4 SRES (Nakicenovic and Swart, 2000), forced by corresponding global and regional climate model inputs. These included three higher-concentration (A2) scenarios with differing initial conditions, and also a moderate concentration (B2) scenario. The model outputs were compared with results from a multimodel ensemble of wave climate projections, in which monthly mean outputs were compiled under the Coordinated Ocean Wave Climate Project (COWCLIP) from four ensemble models (Hemer and Trenham 2015). This considered wave climates for the Mid-Century (2026-2045) and End-Century (2080-2100) under RCP4.5 and RCP8.5, with outputs interpolated to a common global grid at 1.0° x 1.0° resolution.

Table 2. Significant wave height from the ensemble average COWCLIP global simulations, averaged in time over the full simulation periods. For each simulation, the present-day (1975-2009) baseline simulation is compared to Mid- and End-Century projections, with the latter presented as mean wave height, and the mean change and % change from the present-day baseline. This compares mean wave heights derived from 30 years of hourly records using a large sample size, of N>250000, resulting in a value of ±1% being statistically significant at the 95% confidence level.

	baseline	RCP4.5 Mid century			RCP4.5 End century			RCP8.5 Mid century			RCP8.5 End century		
region	mean(m)	mean(m)	Δ(m)	Δ(%)	mean(m)	Δ(m)	Δ(%)	mean(m)	Δ(m)	Δ(%)	mean(m)	Δ(m)	Δ(%)
global	2.34	2.34	0.00	-0.18	2.33	-0.02	-0.64	2.34	0.00	-0.09	2.32	-0.03	-1.11
0	2.79	2.81	0.01	0.50	2.79	0.00	-0.06	2.80	0.01	0.43	2.82	0.03	1.08
1	2.02	2.02	-0.01	-0.23	1.99	-0.03	-1.59	2.01	-0.01	-0.68	1.98	-0.05	-2.43
2	2.40	2.43	0.02	0.98	2.41	0.01	0.27	2.41	0.01	0.41	2.43	0.03	1.34
3	2.42	2.43	0.01	0.44	2.40	-0.02	-0.74	2.41	-0.01	-0.45	2.41	-0.02	-0.67
4	2.96	2.98	0.02	0.71	2.97	0.01	0.26	2.97	0.01	0.39	3.01	0.05	1.52
5	2.38	2.35	-0.03	-1.11	2.31	-0.07	-2.99	2.33	-0.05	-2.09	2.25	-0.13	-5.33
6	2.84	2.84	0.00	0.10	2.79	-0.05	-1.66	2.82	-0.02	-0.70	2.77	-0.07	-2.28
7	3.56	3.60	0.04	1.06	3.60	0.04	1.18	3.61	0.05	1.43	3.70	0.14	3.97

pH

Table 3. Summary of mean present-day pH and projected pH (mean absolute value; Δ = absolute change and % Δ = % change from present day) for Mid- and End-Century for pH and ASH depth under RCP4.5 and 8.5 for the SWP. As pH is the negative logarithm of hydrogen ion concentration, % Δ for pH indicates the percentage change in hydrogen ion concentration (rather than pH).

	Present		RCP2.6			RCP4.5			RCP6.0			RCP8.5		
	day	Period	Mean	Δ	% Δ	Mean	Δ	% Δ	Mean	Δ	% Δ	Mean	Δ	% Δ
pH	8.11	Mid-century	8.03	-0.08	20.2	7.98	-0.12	32.1	7.99	-0.18	30.9	7.93	-0.17	48.3
	8.11	End-century	8.04	-0.07	16.9	7.95	-0.15	42.2	7.89	-0.22	66.0	7.77	-0.33	116.3
ASH	951	Mid-century	746	-186	24.9	717	-215	30.0	733	-199	27.1	692	-240	34.7
depth (m)	951	End-century	685	-248	36.2	598	-340	56.9	549	-383	69.8	337	-595	176.6

Dissolved Oxygen

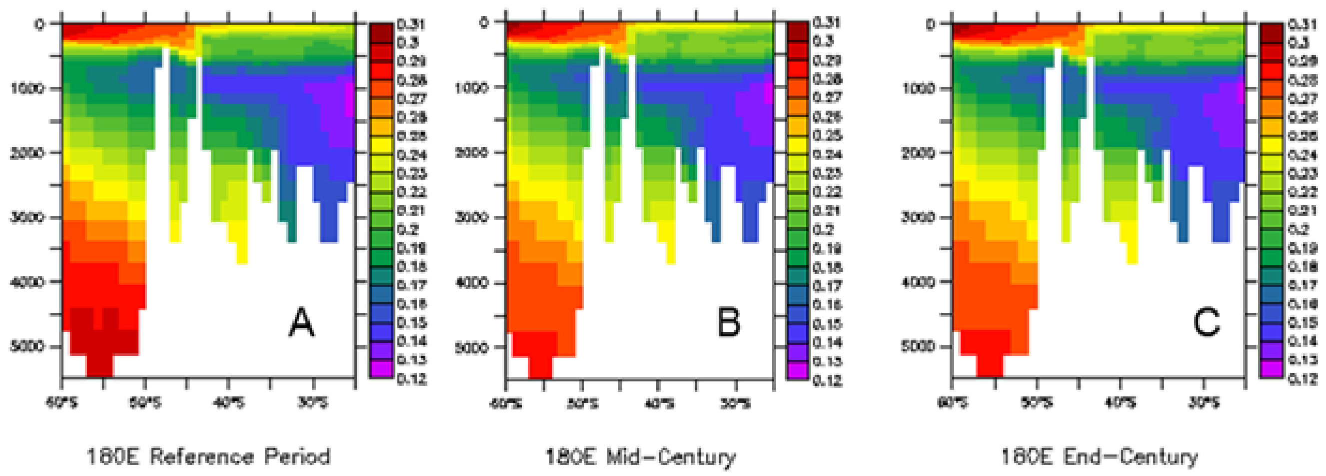

*Figure 5. A meridional transect of the depth-distribution of dissolved oxygen concentration (mmol m^{-3}) east of NZ along 180°E for **A**. the present-day, and projected for **B**. Mid-Century, and **C**. End-Century under RCP8.5 using the GFDL-ESM2G model. Similar results were obtained for a meridional transect along 165°E (data not shown).*

Integrated Primary Production (IntPP)

Comparison of variability of projected IntPP in the different regions of the SWP shows that, as with chlorophyll-a, the Inner ensemble projections show better agreement than the Outer models, although some of the Inner models (Nos. 2 and 13) show larger decreases by End-Century (see Figure 22). All models show a decline in IntPP in Subtropical waters north of NZ in region 1, but conversely increases in IntPP (up to 8 mmol C m^{-2} d^{-1}) in the central Tasman Sea in region 2 and, to a lesser extent (~4 mmol C m^{-2} d-1) over the Chatham Rise, In all other regions, apart from region 7, there is a clear discrepancy between ensembles, with the Inner models showing no change in IntPP whereas the Outer ensemble indicate declining IntPP by End-Century. This reflects major differences in the Inner and Outer ensemble in constraining regional physical and biogeochemical processes, and emphasises the need for robust regional model development for the SWP.

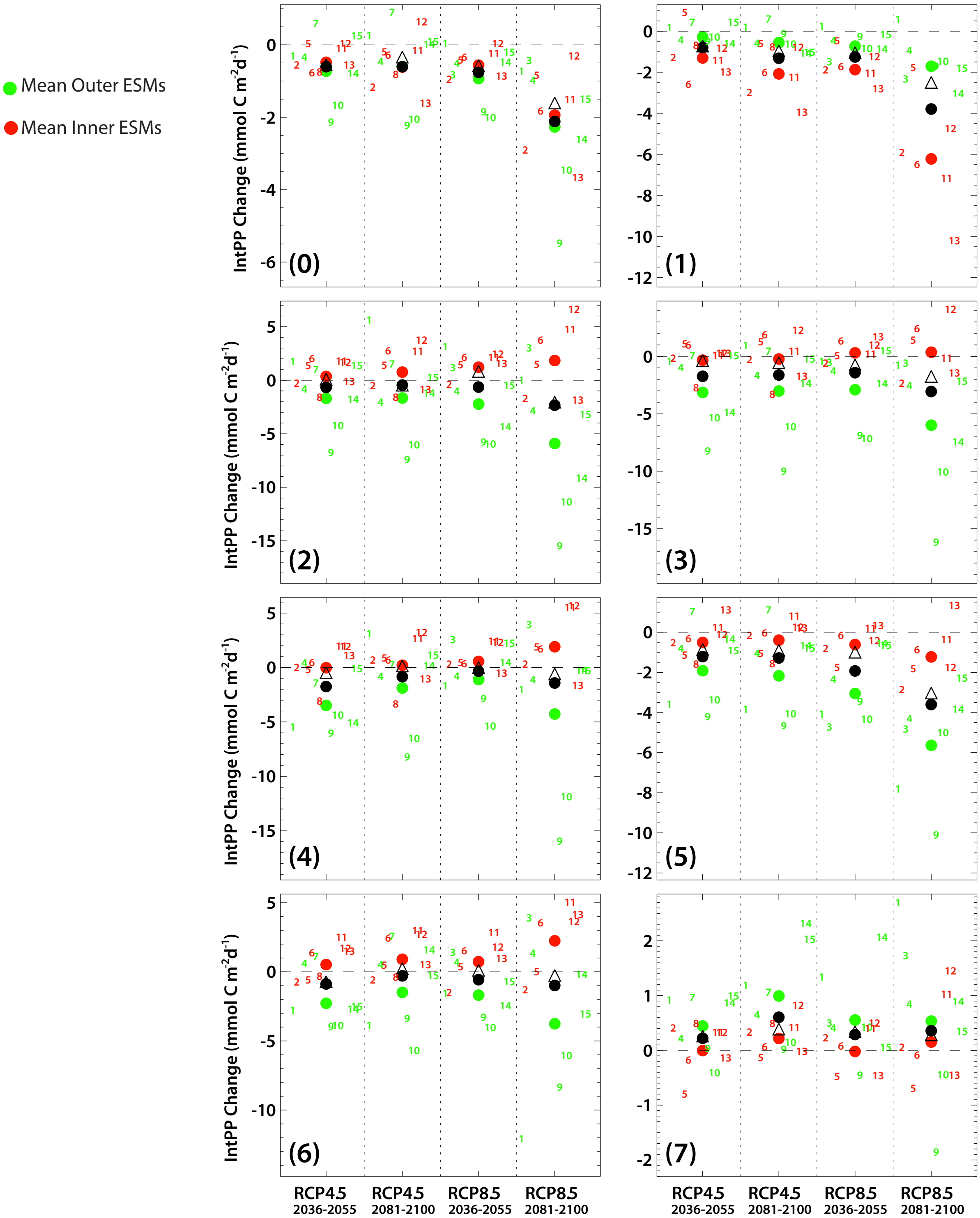

Figure 6. The spatial variation in projected IntPP for the SWP regions (indicated by number, with 0 representing the mean of all regions) for Mid and End-Century under RCP4.5 and 8.5. The Inner and Outer ensemble mean (dots,) and model numbers, are indicated in red and green, respectively. The triangles indicate the mean change of all models.

Flux model

The formulation of Lutz et al. (2007) was used to estimate the passive, vertical flux of particulate organic carbon (POC) to the sea-bed for each spatial pixel in the model domain, with coefficients refitted. The refitted model explains more variance (52% compared to 40%), has less bias and has fewer coefficients (degrees of freedom) than the original model (Lutz et al. 2007, Table 2; average of fits based on SVI and SST). The refitted model also shows improved agreement with data from the NZ Biophysical Moorings north and south of the Chatham Rise in the New Zealand EEZ (Nodder, 2016).

Table 4. CMIP5 Earth System Models used in the flux model, including the respective biogeochemical (BGC) model.

Model	**BGC**	1976-2005	2036-2055		2081-2100	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
CANESM2	CMOC	Y	Y	Y	Y	Y
CESM1BGC	BEC	Y	Y	Y	Y	Y
CNRM-CM5	PISCES	Y	Y	Y	Y	Y
GFDL-ESM2G	TOPAZ2	Y	Y	Y	Y	Y
GFDL-ESM2M	TOPAZ2	Y	Y	Y	Y	Y
GISS-E2-H-CC	NOBM	Y	Y		Y	
GISS-E2-R-CC	NOBM	Y	Y		Y	
HadGEM2-ES	Diat-HadOCC	Y	Y	Y	Y	Y
IPSL-CM5A-LR	PISCES	Y	Y	Y	Y	Y
IPSL-CM5A-MR	PISCES	Y	Y	Y	Y	Y
IPSL-CM5B-LR	PISCES	Y	Y	Y	Y	Y
MPI-ESM-MR	HAMOCC5.2	Y	Y	Y	Y	Y

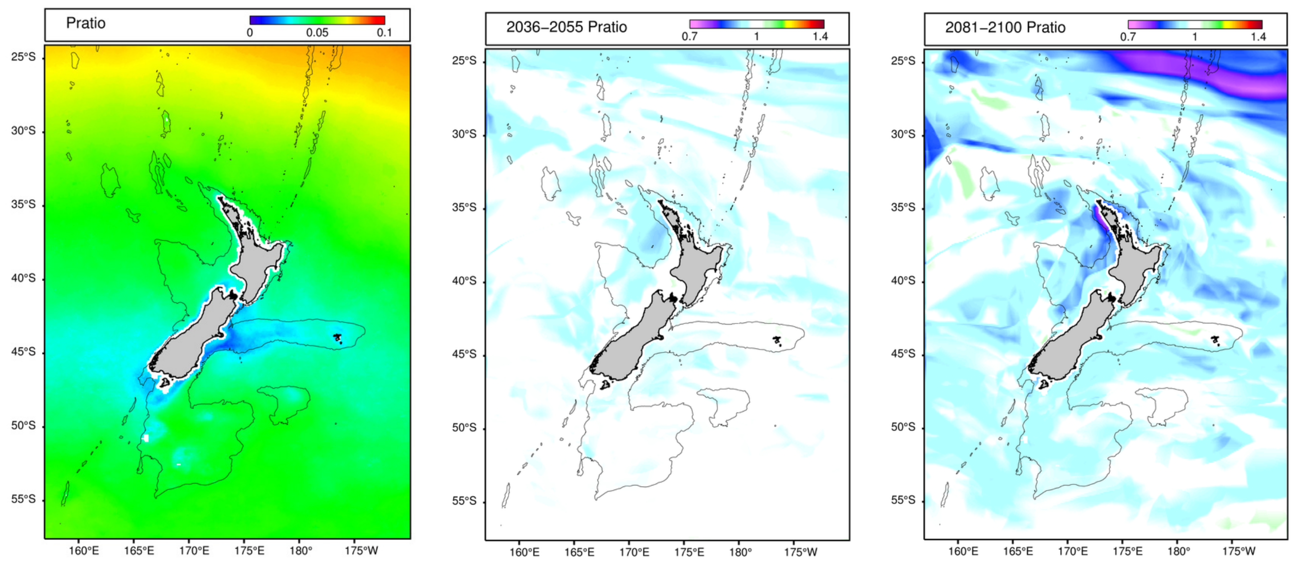

Figure 7. Present-day E-ratio (left panel, dimensionless) and projected future changes in E-ratio at Mid-Century (middle panel) and End-Century (right panel) under RCP8.5. Warm colours indicate an increase and cool colours a decrease, with white indicating no projected change. The 1000m bathymetric contour line is also shown.

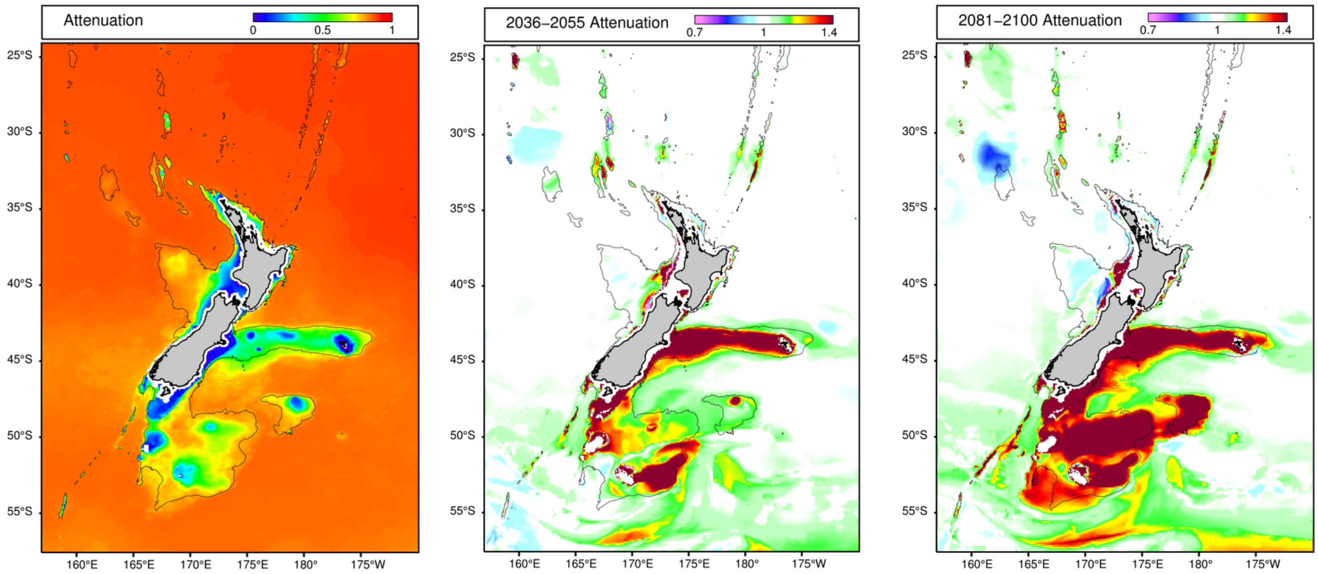

Figure 8. Present-day Flux Attenuation between the surface layer and seabed (left panel, dimensionless), and projected future changes in Flux Attenuation at Mid-Century (middle panel) and End-Century (right panel) under RCP8.5. Warm colours indicate an increase and cool colours a decrease, with white indicating no projected change. The 1000 m bathymetric contour line is also shown.

*Table 5. Projected changes in fluxRelease and fluxSeabed by region and water depth. * indicates significant change greater than the variability (twice the standard deviation) for the present day period.*

Area	**Present day**		**% change**			
	mgC m^{-2} d^{-1}		RCP4.5		RCP8.5	
	mean	Range (2 sd)	Mid Century 2036-2055	End Century 2081-2100	Mid Century 2036-2055	End Century 2081-2100
			fluxRelease			
NZ region	22.6	5.5	-2.4	-4.1	-3.2	-9.1 *
Chatham Rise	23.2	11.6	0.3	-1.0	-0.3	-1.7
Tasman Sea	26.1	6.8	-1.7	-3.2	-3.2	-8.2 *
Subtropical water.	26.7	4.6	-2.8	-7.3 *	-6.4 *	-15.9 *
Subantarctic	17.4	9.6	-0.8	-0.4	-1.1	-0.9
250-800m	21.6	6.9	-1.9	-2.9	-2.4	-7.0 *
800-1500m	23.8	4.8	-2.7	-5.2 *	-3.9	-10.5 *
1500-3000m	25.4	4.3	-3.7	-7.6 *	-6.1 *	-16.4 *
>3000m	21.7	4.6	-2.8	-3.8	-3.7	-10.1 *
			fluxSeabed			
NZ region	4.9	6.8	-4.3	-7.5 *	-7.2 *	-12.5 *
Chatham	9.8	8.5	-6.1	-5.8	-6.3	-10.2 *
Tasman	5.2	9.2	-6.9	-9.1	-8.1	-14.7 *
Subtropical water.	4.4	7.1	-5.8	-8.3 *	-8.0 *	-16.1 *
Subantarctic	4.0	14.1	-5.0	-7.5	-8.1	-12.5
250-800m	7.6	13.0	-5.1	-6.5	-7.0	-12.5
800-1500m	4.0	11.2	-4.2	-7.7	-8.1	-12.6 *
1500-3000m	3.5	6.4	-4.2	-7.7 *	-6.9 *	-15.5 *
>3000m	3.0	6.6	-3.4	-5.0	-5.2	-12.5 *

Impact of changing particle flux on fish species

As particulate flux ultimately provides the food for prey species, it is not surprising that the amount of particle flux at depth has been shown to be positively related to fishery yield over broad spatial and temporal scales (Friedland et al, 2012). In this study we generate a "fish-based" flux (called fluxFish) where the spatial estimates of particle flux are combined with the spatial distribution of specific fish species, and also accounting for the degree to which the feeding mode of each species is pelagic or benthic.

Statistical models (Boosted Regression Trees) based upon catch records from research trawls have been used previously to relate fish species distributions to environmental properties in NZ waters (Leathwick et al, 2006). These models were applied in this study to generate environment-based, spatially comprehensive projections of the future distribution of species across the NZ region. In total, 38 species of fish were assessed, as these met the required criteria for robust prediction of current spatial range (Leathwick et al, 2006b), with an emphasis on commercially-important species in the NZ Quota Management System (QMS).

The particle flux at different depths was merged in proportion to how much of the total diet of each fish species relies on mesopelagic versus benthic feeding. For example, as the diet of hoki on the Chatham Rise is 74% mesopelagic fishes, squid and euphausiids, and 26% demersal fishes and prawns, the *fluxFish* for hoki is:

$$(0.74 \times \mathit{fluxRelease}) + (0.26 \times \mathit{fluxSeabed})$$

The diet proportions estimated for the 38 key fish species were used to calculate *fluxFish* (Dunn et al, 2009), which was then applied to generate projections of change in the prey of these fish in response to climate change using selected models and RCP scenarios as described above.

*Table 6. Changes to fluxFish for key New Zealand fish species (QMS species shown in bold), averaged across both RCP scenarios and both time periods. Species are sorted in decreasing order of change in fluxFish, with a negative change indicating a decrease in fluxFish. A significant change is where the median modal change exceeds the variability in fluxFish during the current period (with the latter taken to be twice the standard deviation of 18 realisations of fluxFish in the present day period between 1998 and 2015 respectively), as indicated by *.*

			Present day *fluxFish* (mgC m^{-2} d^{-1})		**% change**			
			Mean	Range (2 sd)	RCP 4.5		RCP 8.5	
Rank	Code	Name			Mid Cent.	End cent.	Mid Cent.	End cent.
1	NSD	Northern spiny dogfish	15.1	8.4	-10.3 *	-14.7 *	-14.9 *	-24.6 *
2	SKI	Gemfish	17.4	6.8	-8.9 *	-13.5 *	-14.6 *	-22.9 *
3	FRO	Frostfish	18.9	6.3	-8.4 *	-12.1 *	-13.7 *	-22.9 *
4	TAR	Tarakihi	18.7	6.0	-8.6 *	-11.7 *	-13.2 *	-21.8 *
5	WHX	White rattail	6.6	15.4	-8.3	-11.5	-11.9	-14.5
6	SCH	School shark	16.9	5.2	-7.6 *	-9.3 *	-10.8 *	-17.6 *
7	JMD	Horse mackerel	18.5	5.4	-7.3 *	-10.1 *	-10.6 *	-17.2 *
8	EPT	Black cardinal fish	6.2	11.2	-6.9	-8.6	-8.9	-15.0 *
9	SND	Shovelnose dogfish	8.2	16.4	-7.9	-8.4	-9.3	-13.6
10	COL	Olivers rattail	8.6	11.9	-7.4	-7.9	-8.2	-14.9 *
11	SSO	Smooth oreo	4.7	26.5	-6.8	-8.0	-8.7	-14.3
12	CBO	Bollons' rattail	13.4	9.3	-7.2	-7.7	-8.6	-13.9 *
13	WWA	White warehou	12.8	9.2	-7.2	-6.7	-8.1	-14.4 *
14	SWA	Silver warehou	14.1	7.1	-7.0	-6.7	-7.9 *	-14.3 *
15	ORH	Orange roughy	5.6	17.7	-6.3	-7.8	-8.8	-13.0
16	RBM	Ray's bream	13.4	6.9	-6.9	-6.9	-8.1 *	-14.0 *
17	RIB	Ribaldo	6.1	14.9	-6.3	-7.7	-7.9	-13.8
18	LDO	Lookdown dory	12.9	12.5	-8.2	-6.3	-8.2	-12.8 *
19	BSH	Seal shark	10.9	6.8	-5.5	-8.3 *	-7.6 *	-14.0 *
20	HAK	Hake	7.7	13.0	-6.6	-7.3	-7.7	-13.8 *
21	HOK	Hoki	10.2	10.4	-6.8	-6.7	-7.6	-14.2 *
22	SPE	Sea perch	14.4	9.5	-7.1	-6.4	-8.3	-12.8 *
23	HAP	Hapuku	16.1	5.2	-6.0 *	-6.7 *	-6.8 *	-14.5 *
24	RBT	Redbait	15.3	5.3	-6.3 *	-6.7 *	-7.1 *	-13.6 *
25	RCO	Red cod	15.6	5.4	-5.8 *	-7.2 *	-7.1 *	-13.0 *
26	SPD	Spiny dogfish	13.4	7.2	-5.9	-6.5	-7.1	-13.5 *
27	JMM	Murphy's mackerel	15.4	5.3	-6.0 *	-6.9 *	-6.9 *	-13.1 *
28	SOR	Spiky oreo	9.2	21.6	-7.4	-6.5	-7.4	-11.1
29	BNS	Bluenose	20.0	5.1	-4.1	-7.1 *	-5.8 *	-14.0 *
30	JAV	Javelin fish	7.4	16.1	-5.6	-6.2	-7.3	-11.8
31	GSP	Pale ghost shark	7.1	17.9	-5.5	-6.5	-7.2	-11.2
32	LIN	Ling	8.1	14.9	-4.8	-6.3	-7.2	-12.0
33	LSO	Lemon sole	14.7	14.7	-6.7	-5.4	-6.0	-11.8
34	BYX	Alfonsino	14.4	9.0	-5.7	-5.3	-6.1	-10.8 *
35	WAR	Blue warehou	16.0	6.2	-4.7	-6.0	-5.6	-11.3 *
36	SBW	Southern blue whiting	6.0	34.4	-4.2	-4.6	-6.4	-8.5
37	BAR	Barracouta	22.6	8.6	-3.2	-4.9	-4.3	-8.3
38	BOE	Black oreo	12.3	11.5	-2.2	-2.9	-3.3	-5.7

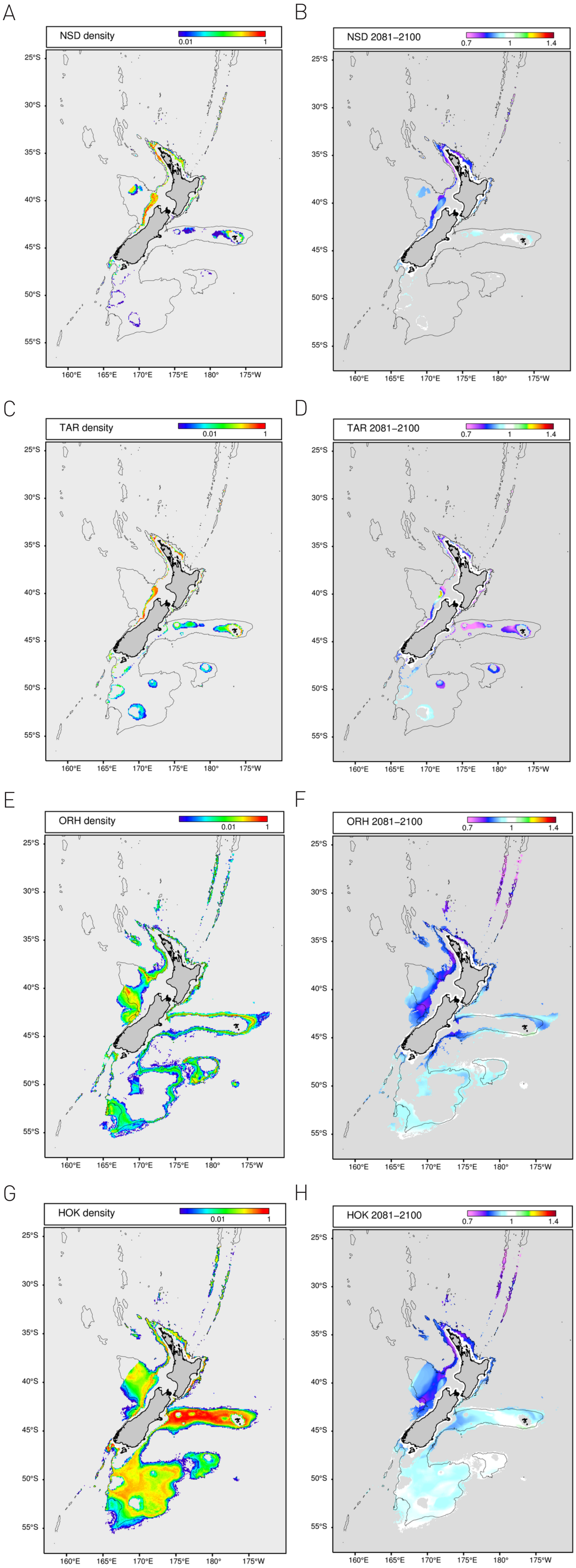

*Figure 9. Projected distribution of selected fish species in present-day (left panels) and median change in fluxFish (right panels) for these species under RCP8.5 by End-Century (2081–2100) for **A** and **B**. Northern Spiny Dogfish; **C** and **D**. Tarakihi; E and **F**. Orange Roughy; and **G** and **H**. Hoki. Where cooler colours indicate a decline.*

Cold Water Corals

Present-day and future distributions of cold water corals within the NZ region were estimated using Boosted Regression Tree (BRT) models, with key variables selected from a suite of candidate models that included bottom water temperature, salinity, sea surface height; concentrations of aragonite, calcite, dissolved oxygen, dissolved inorganic carbon, nitrate, and chlorophyll-a, plus bathymetric slope and seamount. The modelled Cold Water Coral taxa included four species of reef-building scleractinians (stony corals), four genera of gorgonian octocorals, and four genera of black corals. This analysis and interpretation is discussed in full in Anderson et al (2016).