

Ocean Acidification Assessment

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Version 1.1	Minor Amendments to update number, dates and location of Sampling Sites, and the new website (https://nzodn.nz/portal/)	8 July 2022

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Executive summary

NIWA has been requested by the Ministry for the Environment and Statistics New Zealand (Stats NZ) to provide an updated dataset and associated report for the ocean acidification environmental indicator, for inclusion in the *Environment Aotearoa 2022* (EA22) report.

Ocean acidity data from the Munida Time Series for the years 1998 to 2020 was provided, and data from a subset of nine sites from the New Zealand Ocean Acidification Observing Network (NZOA-ON) for the years 2015 – 2021 are to be downloaded directly from the New Zealand Ocean Data Network website (<https://nzodn.nz/portal/>) by Stats NZ.

This report summarises the methods and calculations used for both data sets, provides an analysis of the trends and variability, and discusses the implications of this for the New Zealand marine environment.

The data are used to report towards the United Nations Sustainable Development Goal 14.3 and have been included in the World Meteorological Organisation State of the Global Climate reports.

Key findings:

- Ocean acidity in sub-antarctic waters near New Zealand increased by an average of 8.6 % over the 23 years from 1998 to 2020. This is within the range observed at other open ocean sites around the world.
- Ocean acidification at the coastal sites has not been measured for long enough for any long-term trend to be resolvable from the natural shorter-term variability. This is similar to what is seen at coastal sites in Japan, Bermuda and the USA. New Zealand coastal measurements started in 2015, and, given the range of factors causing variation in acidity in this environment, it would take more than 58 years for any long-term trends to become apparent under the current sampling regime.
- Factors influencing ocean acidification at the coastal sites include water temperature, freshwater and terrestrial input, biological activity, and currents and tides.

1 Description of Services

The Ministry for the Environment and Stats NZ are required to report on the state of the environment under a 3-yearly cycle, using a pressure-state-impact framework, by the Environmental Reporting Act 2015. These states of the environment reports are delivered under the Environmental Reporting Programme (the Programme). Every three years the Programme releases a 'synthesis' report – bringing together the data and findings from across the different domain reports. A new synthesis report, *Environment Aotearoa 2022* (EA22), was published in April 2022, although indicator webpages and data were to be released by the end of 2021.

Ocean acidification is one of the marine environmental indicators, and the dataset will be updated for EA22.

The data from the Munida time-series was provided and the NZOA-ON are to be downloaded directly from the New Zealand Ocean Data Network website (<https://nzodn.nz/portal/>) by Stats NZ, and are not required to be provided with the written report.

This written report on ocean acidification and ocean acidification data from the Munida time-series transect and the New Zealand Ocean Acidification Observing Network (**NZOA-ON**) comprises the second part of the report and includes:

- Methods, calculations and key trends for both data sets.
- Discussion of what the data is telling us about acidification of our oceans.

2 Methods, calculations, and key trends

Ocean acidification data for the period 1998 to 2020 have been used to construct the indicator.

Surface pH values (on the total scale) in the Munida time-series were calculated from measured dissolved carbon dioxide ($p\text{CO}_2$) and alkalinity using refitted Mehrbach constants, at the *in situ* temperature, (Mehrbach et al. 1973; Dickson and Millero 1987). Acidity (hydrogen ion concentration) values were determined for each voyage over the time period, and a linear regression fitted to these values. The equation of that linear regression was evaluated to calculate the % increase in acidity, as per the methodology applied in 2019.

The pH values for the NZOA-ON dataset were calculated from measured dissolved inorganic carbon concentration (DIC) and measured alkalinity at the *in situ* temperature, using refitted Mehrbach constants (Mehrbach et al. 1973; Dickson and Millero 1987).

2.1 Methods and calculations: Munida Time Series

The Munida Time Series is a programme measuring marine carbonate chemistry in the waters associated with the sub-tropical front on the Otago Shelf, south-east New Zealand. The surface transect extends from Taiaroa Head (170.72 °E -45.77 °N), 65 km offshore to 171.53 °E -45.83 °N, traversing neritic, modified subtropical, frontal and sub-antarctic waters, with a deep station (1000m) in subantarctic water at the eastern end of the transect. Voyages have been conducted every two months since January 1998, with continuous surface measurements of temperature (T), salinity (S), and partial pressure of carbon dioxide ($p\text{CO}_2$), and measurements of total alkalinity (A_T) on discrete samples taken at nine surface stations located equidistant along the transect. Other parameters are also measured, and short-term projects on a variety of subjects are included in the Munida Time Series programme but will not be presented or discussed here.

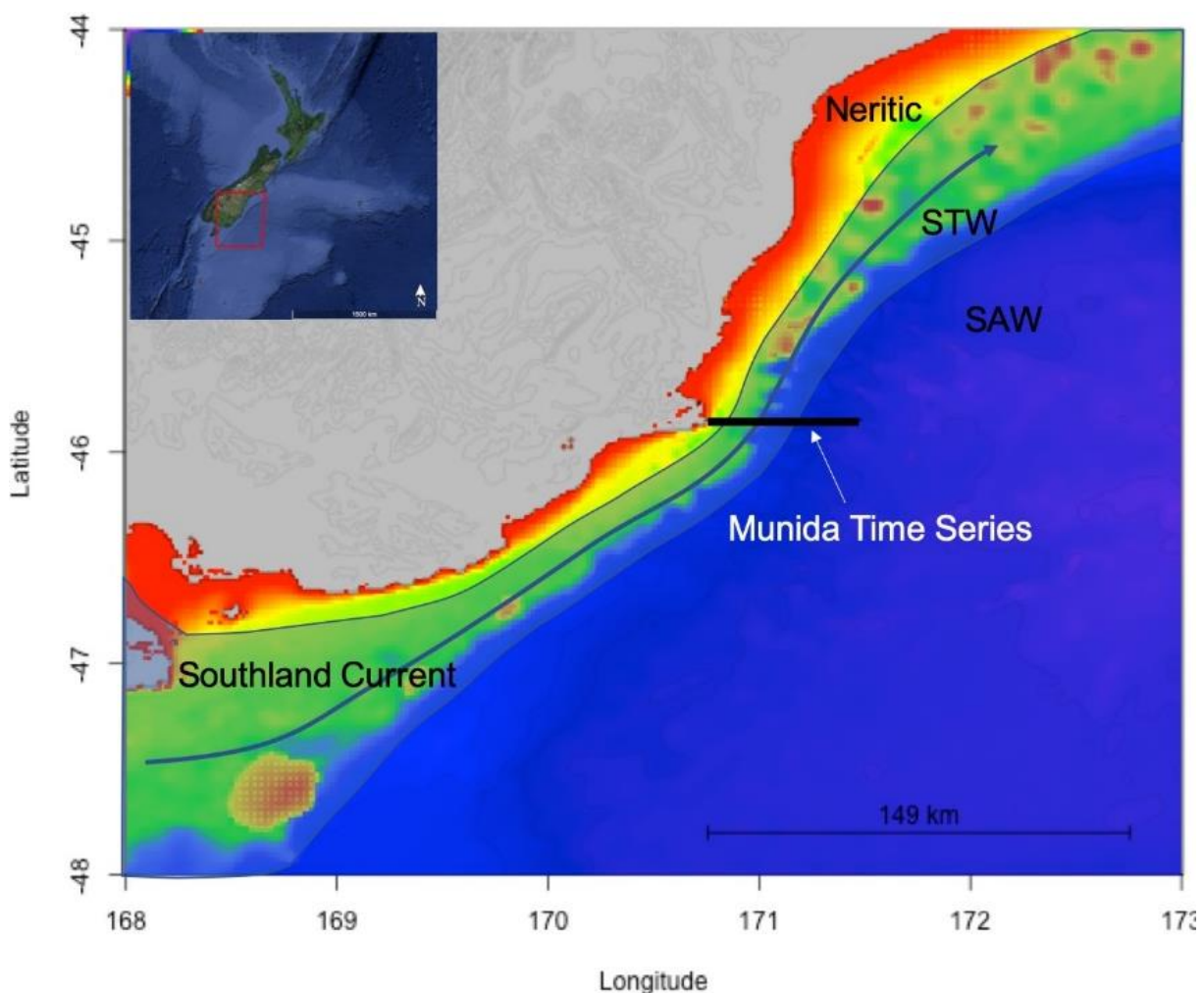


Figure 1: Location of the Munida Time Series Transect. extending 60 km from coast through neritic waters, the subtropical (STW) of the Southland Current and into the subantarctic waters (SAW). After Vance et al. (2019).

The ocean acidification data and analyses presented here are for sub-antarctic water, located at the eastern end of the time series transect. Sub-antarctic water is defined by the temperature and salinity characteristics of the water, and in general is located at distances greater than 50 km from Taiaroa Head. Continuous surface data (T, S, $p\text{CO}_2$) are averaged into 0.5 km bins, then these are

averaged to give one sub-antarctic value per voyage. The discrete sample data (A_T) are averaged to give one sub-antarctic value per voyage (generally two or three samples per voyage).

pH is calculated on the total scale at the *in situ* temperature from the measured $p\text{CO}_2$ and alkalinity, temperature and salinity, using the refitted Mehrbach constants (Mehrbach et al. 1973; Dickson and Millero 1987). The calculations are done using the software SWCO2 (Excel add-in version).

Missing values:

Missing salinity: The alkalinity analysis uses salinity in the calculation but is not sensitive to it, resulting in a small error. pH calculated from alkalinity and $p\text{CO}_2$ uses salinity but is not sensitive to it. Therefore, if a measured salinity value was not available, a value of 34.3 was used, this being the average value at this site over the time period 1998 – 2020 ($\sigma = 0.1$) and typical of subantarctic water at this location.

Missing $p\text{CO}_2$: Calculated pH is very dependent on $p\text{CO}_2$, so if a $p\text{CO}_2$ value was missing the pH was not calculated.

Missing alkalinity: Calculated pH is slightly dependent on alkalinity. Therefore, if an alkalinity value was missing, an average of the alkalinity for the sub-antarctic water from the preceding and subsequent voyages was used in the pH calculation.

The hydrogen ion concentration ($[\text{H}^+] / \text{mol kg}^{-1}$) for each voyage was determined from the pH using Equation (1)

$$[\text{H}^+] = 10^{-\text{pH}} \quad (1)$$

A linear regression was fitted to the hydrogen ion time series from 1 January 1998 to 31 December 2020, using data from 127 voyages spanning 20 January 1998 to 23 November 2020 (first and last voyage of time period, ensuring that a complete year of data is included, so as to avoid biases resulting from different phases of the seasonal cycle). The equation of the linear regression was evaluated using the Excel Data Analysis Toolpak.

Trends were then determined over the full 23-year time-period from 1 January 1998 to 31 December 2020 by extrapolation of the linear regression equation. The values determined from the linear regression are termed “modelled values”, and those directly measured are termed “measured values”.

2.2 Trend in Acidity (hydrogen ion concentration): Munida Time Series

The Time of Emergence, defined as the length of time that it will take before a long term trend will emerge from the seasonal and inter-annual variability (Turk et al. 2019), is 13 years at this sub-antarctic site (Vance et al. 2019). This means that any long-term trend would be detectable at this site from 2011, and so evaluation of a long-term trend in acidity (hydrogen ion concentration) is possible. As pH is a log-scale it is more robust to report trends in acidity as changes in hydrogen ion concentration rather than changes in pH. A more robust examination of the long-term trend would include seasonal detrending and a rigorous error analysis (Carter et al. 2019; Sutton et al. 2019), and is beyond the scope of this report.

The time series of acidity (hydrogen ion concentration) is given in Figure 2, with the linear regression statistics given below the figure. Extrapolation of the linear regression (Figure 2) to 1 January 1998

and 31 December 2020 gives an average 8.6 % increase in acidity (hydrogen ion concentration) over the 23 years.

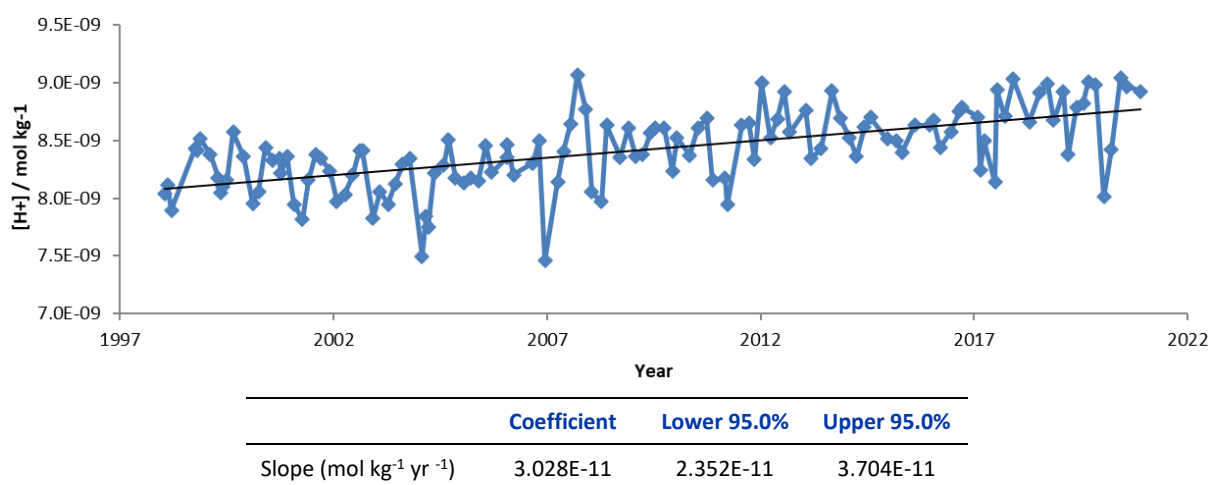


Figure 2: Acidity of subantarctic water, 1998 - 2020. the hydrogen ion concentration (mol kg⁻¹) from 127 voyages spanning 20 January 1998 to 23 November 2020, fitted with a linear regression. Time is in decimal year. The regression statistics are given in the table below the Figure.

2.3 Key Findings: Munida Time Series

The pH has decreased by 0.036 units in the 23 years, from a modelled value of 8.092 on 1 January 1998, to 8.057 on 31 December 2020, this is equivalent to an 8.6% increase in acidity (increase in hydrogen ion concentration). The pCO₂ in the surface waters increased from a modelled value of 349.9 μatm on 1 January 1998, to 384.9 μatm on 31 December 2020, an increase of 35.0 μatm over the 23 years, at an average rate of 1.5 μatm per year (Table 1). The average global increase in atmospheric carbon dioxide for the decade 2010-2019 was 2.4 ppm yr⁻¹.

Table 1: Trends in modelled ocean acidity parameters at the Munida Time Series sub-antarctic site. The values were determined using the linear regression equations fitted to the measured data and evaluated for 1 January 1998 and 31 December 2020.

	Trend (yr ⁻¹)	1 January 1998	31 December 2020	change	% change
Hydrogen ion concentration (mol kg ⁻¹)	+ 3.028*10 ⁻¹¹	8.080*10 ⁻⁹	8.777*10 ⁻⁹	6.963*10 ⁻¹⁰	8.6
pH	- 0.0016	8.092	8.057	-0.036	
pCO ₂ (μatm)	+ 1.5	349.9	384.9	35.0	10.0

2.4 Methods and calculations: New Zealand Ocean Acidification Observing Network (NZOA-ON)

The NZOA-ON consists of 30 sites around the New Zealand coastline, including 9 sites in collaboration with the Department of Conservation, and 5 sites managed by Environment Waikato. Sampling initially started with 10 sites in 2015, other sites have subsequently joined the network, and several have been discontinued or are on hold. A subset of 9 sites is considered here, the same sites as were presented in the 2019 Environmental Indicator update (Table 2).

Table 2: NZOA-ON sample site details. The latitude and longitude, time of emergence (ToE) and main driver of the acidity of the sites considered in this report. *Vance et al. (2019).

Site	Location of data collection	ToE / years*	Main driver*
Auckland	Chelsea Point -36.823 °N 174.724 °E	73	water temperature
Bay of Plenty	Toll Marina, Tauranga -37.669 °N 176.1774 °E	60	water temperature
Chatham Islands	Waitangi Wharf -43.946 °N 176.560 °W	95	mixed
Dunedin	Pylon 1A, Taiaeroa Head -45.780 °N 170.720 °E	72	mixed
Marlborough	Cannon Hill -40.946 °N 173.987 °E	79	mixed
Stewart Island	Ulva Island wharf -46.925 °N 168.131 °E	85	mixed
Tasman Bay	Cawthron Aquaculture Park -41.191 °N 173.349 °E	64	water temperature
Wellington	Greta Point, Evans Bay 41.301 °N 174.808 °E	58	mixed
West Coast	Jackson Bay wharf -43.973 °N 168.616 °E	61	freshwater input

Sampling Partners collect bottle samples of seawater following a standardised protocol in which they are trained and also auxiliary information including water temperature. The preserved samples are analysed at a central laboratory for the concentration of dissolved inorganic carbon (DIC) and total alkalinity (A_T) following the method of Dickson et al (2007).

pH was calculated on the total scale at the *in situ* temperature from the measured DIC and alkalinity, temperature and salinity, using the refitted Mehrbach constants, (Mehrbach et al. 1973; Dickson and Millero 1987). The calculations were done using the software SWCO2 (Excel add-in version). These data for the period 2015 to 2021, along with data from the other NZOA-ON sites, are available from the New Zealand Ocean Data Network website (<https://nzodn.nz/portal/>). Detailed information on sampling and analysis procedures is available at the NIWA website (<https://niwa.co.nz/coasts-and-oceans/research-projects/new-zealand-ocean-acidification-observing-network-nzoa-on>).

Missing Values: pH is only calculated for samples with DIC, alkalinity, temperature and salinity data.

2.5 Trends in Acidity (hydrogen ion concentration): NZOA-ON

The seasonal and interannual variability of the acidity at the coastal sites is much larger than that of the Munida open ocean site. Therefore, the Time of Emergence, the time required for a long-term

signal to emerge from the short term variability, is much longer for the coastal sites than for the open ocean, such as at the Munida sub-antarctic site (Table 2). The Time of Emergence for the coastal sites ranges from 58 years (Wellington) to 95 years (Chatham Islands) (Vance et al. 2019). The NZOA-ON time series is too short for any long-term trends to be resolvable at any of the sites.

2.6 Key Findings: NZOA-ON

The variability at each site is dependent on the drivers of the carbonate chemistry at each site, including water temperature, biological activity, water mixing and interactions with the land, (e.g., riverine input, point sources) (Vance et al. 2019). Each of these drivers vary on daily, seasonal, annual, and inter-annual time scales, and the magnitude and relative importance of each varies from site to site (Table 2). In general, the major driver at a particular location can be deduced from a knowledge of the ecosystem type and physical regime. Removing the temperature variability from the pH calculation (i.e., normalising to the mean annual temperature for a site) allows identification of sites where the seasonal water temperature change is the main driver (Auckland, Bay of Plenty, Tasman Bay). The influence of dilution by freshwater such as riverine input and high rainfall can be determined from salinity – alkalinity and salinity- DIC mixing diagrams (West Coast). An estimate of biological activity requires more information than simply the carbonate chemistry data collected in the NZOA-ON programme, and sites that have multiple significant drivers require a deconvolution or modelling approach to tease out the relative effects of changing water temperature, biological activity, water mixing and terrestrial interactions as well as the input of atmospheric carbon dioxide.

The Times of Emergence for all of the NZOA-ON coastal sites are greater than the duration of the monitoring, so no long-term changes can be seen at any of the locations. This is similar to what is seen at coastal sites globally where the observation times are not yet long enough to see any long-term trends.

3 Discussion

3.1 Global trends in ocean acidity

Long term programmes monitoring marine carbon parameters at open ocean sites began in the 1980s, initially to research the role of the ocean in the global carbon cycle. The same parameters measured for this purpose can now be interpreted through the lens of ocean acidification. Long-term sustained observations at several additional sites, including the Munida Time Series in the southern hemisphere, have subsequently added to the global understanding of marine carbon dynamics. More recently, moorings and repeat ship-based occupations at coastal sites have been implemented by many countries, often as part of ocean acidification observation programmes. A summary of ocean acidity at open ocean and coastal time series stations is given in Table 3.

A synthesis of the data from open ocean time series stations (Bates et al. 2014), including the Munida Times Series sub-antarctic site, included data up to 2012. This showed similar trends in both $p\text{CO}_2$ and pH at the 7 sites included, despite their location in diverse oceanic environments, reflecting the uptake of anthropogenic carbon dioxide.

Variability in the carbon chemistry of the Sargasso Sea (including pH) on decadal time scales is now evident in the 31 year long time BATS data, and a recent acceleration of the change has been observed (Bates and Johnson 2020). Changes in the ocean biology and physics at the site are evident from changes in temperature, salinity and oxygen content, and oceanic uptake of anthropogenic

carbon dioxide has substantially changed the ocean carbon chemistry at this site (Bates and Johnson 2020) (Table 3).

Ocean acidification at 289 coastal sites in Japan was determined for the years 1978 to 2009 (Ishizu et al. 2019). Both positive and negative (annual average pH increased at 30 % of the sites) trends in acidification were observed, with average summer pH decreasing at 70% of the sites, and increasing at 30% of the sites, and average winter pH decreasing at 75 % of the sites and increasing at 25 % of the sites.

An analysis of pCO₂ data from 40 surface buoys moored in open ocean, coastal and coral reef waters from the Pacific (29 sites), Atlantic (9 sites), Indian (1 site) and Southern Ocean (1 site) basins showed that only those at open ocean sites have been operating long enough to detect an anthropogenic trend (Sutton et al. 2019). The estimated times of emergence of the long-term trend at the coastal sites range from 16 to 41 years, and at coral reef stations range from 9-22 years. These are greater than the duration of the deployments, so no trends were reported for these sites.

Synthesis and characterisation of long-term pH changes at 83 coastal sites from 11 regions of the world (Carstensen and Duarte 2019) revealed a broad span of trends ranging from -0.023 pH units per year (ie increasing acidity, 55% of the sites) to +0.023 pH units per year (ie decreasing acidity), with large errors in the trends at each site due to both measurement uncertainty and large seasonal and inter-annual variability. Much of the variability was driven by changes in terrestrial inputs such as freshwater, nutrients and organic matter.

Table 3: Trends in pH and pCO₂ at open ocean, coastal and coral reef sites. References: (1) this report; (2) Bates et al. (2014); (3) Bates,Johnson (2020); (4) Sutton, A J et al. (2017); (5) Evans et al. (2020); (6) Wakita et al. (2017); (7) Midorikawa (2010); (8) Bates (2017); (9) Ishizu et al. (2019); (10) Carstensen, Duarte (2019).

Site	Location	pCO ₂ ($\mu\text{atm yr}^{-1}$)	pH (yr^{-1})	Duration	Reference
This report					
Munida	SW Pacific	1.5	-0.0016	1998 - 2020	1
Open Ocean					
Iceland Sea	Iceland Sea	1.29	-0.0014	1983 - 2012	2
Irminger Sea	Irminger Sea	2.37	-0.0026	1983 - 2012	2
BATS	Sargasso Sea	1.69	-0.0017	1983 - 2012	2
		1.92	-0.0019	1983 - 2019	3
ESTOC	Canary Islands	1.92	-0.0018	1995 - 2012	2
HOT	Equatorial Pacific	1.72	-0.0016	1988 - 2012	2
CARIACO	E Venezuela Basin	2.95	-0.0025	1995 - 2012	2
Munida	SW Pacific	1.28	-0.0013	1998 - 2012	2
WHOTS	Equatorial Pacific	2.4	-0.002	2004 - 2013	4
Stratus	SE Pacific	2.0	-0.002	2006 - 2015	4
KEO	NW Pacific	1.2	-0.001	2007 - 2014	4
Papa	NE Pacific	1.6	-0.001	2007 - 2014	4
Alaska	Bering Strait	-0.7		1989 – 2018	5
	Unimak Pass	2.2		1995 – 2019	
	Kenai Peninsula	5.1		2012 - 2019	
K2, NW Pacific Ocean	NW Pacific	2.13	-0.0025		6
North Pacific Open Ocean	N Pacific		-0.0013 (summer) -0.0018 (winter)		7
Coastal and Coral Reef Sites					
Harrington Sound	Bermuda coral reef	5.4	-0.0046	1996 - 2016	8
289 sites average	Japan coastal		-0.0014 (summer) -0.0024 (winter)	1978 - 2009	9
83 coastal sites	Global synthesis		-0.023 to +0.023	Variable, 6-67 years	10

3.2 Current international work to synthesise ocean carbon time series data sets

Marine carbon data from 11 ship-based time series stations around the globe are being synthesised, as part of a European Horizon 2020 funded initiative, and includes data from the Munida Time Series. This project involves standardisation of calculations and quality control procedures to produce an internally consistent assessment of ocean acidification parameters and how they are changing in different marine environments.

The development of ecological and biogeochemical data and metadata standards for shipboard time series data sets is also the focus of the US led Marine Ecological Time Series (METS) Research Coordination Network (RCN) (<https://www.us-ocb.org/ocb-to-lead-nsf-funded-earthcube-research-coordination-network-for-marine-ecological-time-series-mets-rcn/>). NIWA's Dr Kim Currie is a member of the Steering Committee for the METS RCN.

3.3 Reporting towards the Sustainable Development Goal 14.3

In 2015, the United Nations adopted the 2030 Agenda and a set of Sustainable Development Goals (SDGs), including a goal dedicated to the ocean, SDG 14, which calls to "conserve and sustainably use the oceans, seas and marine resources for sustainable development". Ocean acidification is specifically included in SDG Target 14.3: "Minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels", and the associated indicator which calls for the "Average marine acidity (pH) measured at agreed suite of representative sampling stations".

Data and metadata from the Munida Time Series and the NZOA-ON coastal sites comply with the reporting requirements, and have been submitted to the UN via the [SDG 14.3.1 Data Portal](#), in January 2020 and February 2021.

3.4 World Meteorological Organisation

The WMO included ocean acidification as a Global Climate Indicator in 2018. The New Zealand data were mentioned in the WMO Statement on the State of the Global Climate in 2018 (WMO 2019), and featured in the 2019 Report (WMO 2020).

3.5 Drivers of observed trends

The main factors influencing marine carbon chemistry are summarised in Table 4. They each vary on temporal and spatial scales, for example, seasonal water temperature changes, seasonal changes in biological activity (e.g. spring blooms), tidal mixing, daily photosynthesis within a kelp bed. Therefore, at a particular location, resulting changes in pH will depend on the relative importance of each driver at a particular time, and the combined effects of those drivers. Usually, it is difficult to separate out the individual drivers without additional supporting information, such as measurements of biological carbon fixation, current velocity, or upwelling rates.

Table 4: Drivers of seawater acidity. The effect of the change in the driver on the pCO₂, pH and acidity is indicated by ↑ (increase) or ↓ (decrease).

	Driver	pCO ₂	pH	Acidity
Temperature	↑	↑	↓	↑
Biological Activity	photosynthesis ↑	↓	↑	↓
	respiration ↑	↑	↓	↑
Atmospheric Exchange	absorption	↑	↓	↑
	de-gassing	↓	↑	↓
Water mixing	upwelling	↑	↓	↑
	currents	variable	variable	variable
Calcium carbonate formation / dissolution	formation	↑	↓	↑
	dissolution	↓	↑	↓

Increasing seawater temperature will cause an increase in pCO₂ and a decrease in pH. Oceanic uptake of atmospheric carbon dioxide can be positive (absorption) or negative (de-gassing) depending on the relative concentration of carbon dioxide in the surface water and the overlying atmosphere. Oceanic exchange includes both ‘natural’ and anthropogenic carbon dioxide. Water mixing can be horizontal or vertical, and can be due to currents, upwelling, downwelling and eddies. The resulting change in carbon chemistry depends on the relative concentration of the mixing components and their relative volume, as well as the physical characteristics of the mixing end-members such as temperature.

Inputs of nutrients, organic and inorganic carbon from terrestrial sources to coastal environments can result in excessive production of algae, a process called eutrophication. When these algae die and sink, the microbial activity decreases the oxygen concentration, increases the carbon dioxide concentration and increases the acidity of the water (Wallace et al. 2014). The interaction between atmospheric carbon dioxide uptake and eutrophication can reduce the buffer capacity of the water, thereby further increasing the susceptibility of these waters to ocean acidification, such as in the Gulf of Mexico and the East China Sea (Cai and Xinping Hu 2011). Calcium carbonate mineral cycling can also locally buffer the pH decrease caused by aerobic respiration and anthropogenic carbon dioxide, as seen at Chesapeake Bay, USA (Su et al. 2020). High nutrient loading in the Firth of Thames, New Zealand, results in phytoplankton blooms in spring and early summer then respiration and oxygen depletion in summer and autumn, with a decrease in pH at some locations (Law et al. 2018).

Photosynthesis in kelp beds and seagrass meadows draws down carbon dioxide in the water, locally increasing the pH, and providing a buffer for organisms living in the immediate environment (Bergstrom et al. 2019).

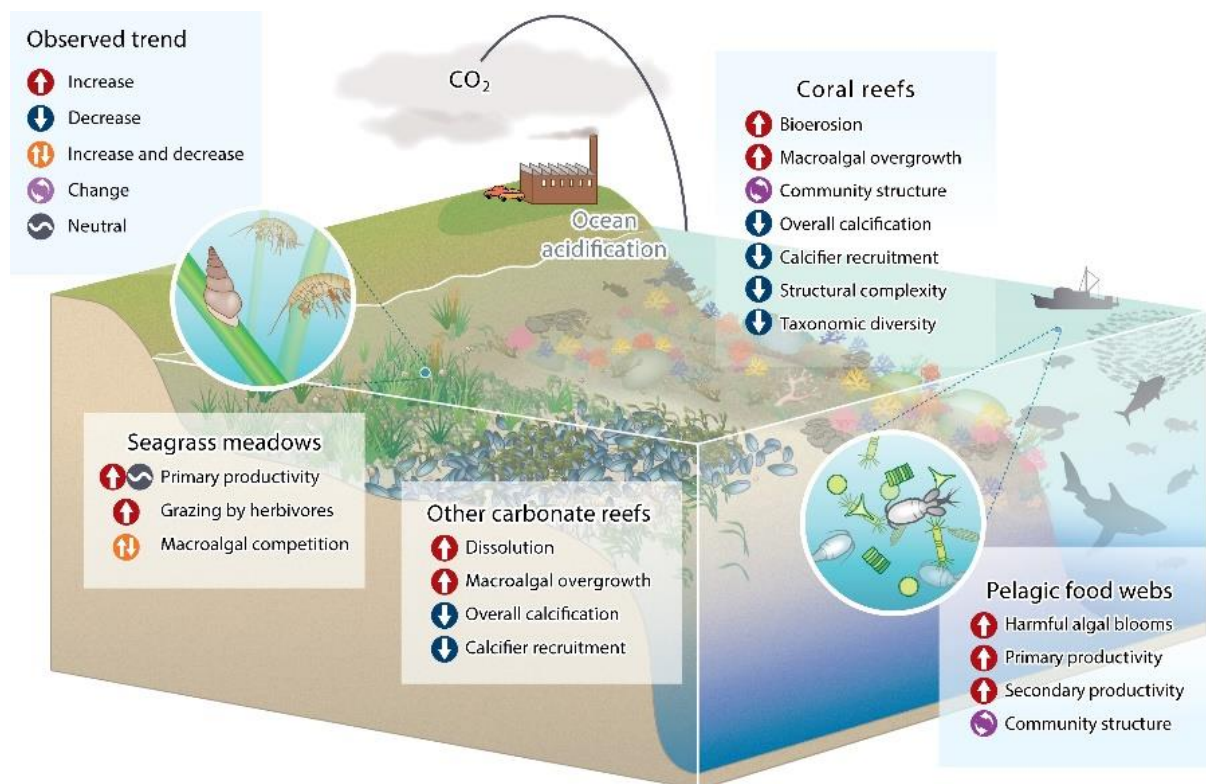
3.6 Ocean acidification in a multi-stressor environment

Coastal and oceanic environments are subject to many anthropogenic and natural stressors, and ocean acidification is only one pressure. Ocean warming, coastal pollution, de-oxygenation, changing nutrient and light levels are some of the pressures that affect marine plants and marine animals at the individual, species and ecosystem levels. The impact of these multi stressors are generally non-linear and they may can act synergistically (combined effect is greater than the individual effects) or

antagonistically (combined effect is less than the individual effects) (Kroeker et al. 2017). It is difficult to separate out the individual effects in natural systems where multiple stressors occur, though in general the overall combined stress is what is ecologically important. The West Coast Ocean Acidification and Hypoxia Science Panel report on multiple stressors includes a useful table of potential multi-stressor perturbation scenarios (Hales et al. 2015).

3.7 Biological implications of increasing ocean acidity

Biological responses of individuals to changes in ocean acidity depend on species, life stage, and environment, as well as individual characteristics such as resilience and life history. Reported effects include changes in energy redistribution, metabolism, physiology, behaviour and sensory perception, with additional effects at population, community and ecosystem levels. In general, early life stages are more vulnerable to high carbon dioxide-low pH conditions; calcifying species such as shellfish, corals and coralline algae are vulnerable; photosynthesising organisms (seaweed) will generally benefit. The general trends in key community and ecosystem responses to ocean acidification are presented in a review by Doney et al (2020) and summarised in Figure 3.



Doney SC, et al. 2020. *Annu. Rev. Environ. Resour.* 45:83–112

Figure 3: Trends in community and ecosystem properties under a high CO₂ environment. Figure 3 from Doney et al (2020). See the original for references to the studies on which this figure is based. Reproduced under Creative Commons Attribution 4.0 International License.

Law et al. (2018) provide a comprehensive assessment of the potential vulnerability of New Zealand marine species to ocean acidification. Table 5 is a summary of the current state of knowledge of aspects of ocean acidification research for the major biotic groups in New Zealand waters.

Table 5: Assessment of the vulnerability and current knowledge of New Zealand marine organisms to ocean acidification. (-) no studies have been carried out, (+) ongoing studies (in 2017), (*) studies were part of the CARIM project. Reproduced from Law et al. (2018), Table 3.

	Heterotrophs		Primary Producers		Primary and Secondary Consumers					Tertiary Consumers	Higher Trophic
	Bacteria	Phytoplankton	Macroalgae	Bryozoa	Sponges	Cold Water Corals	Crustacea	Molluscs	Echinoderms	Fish	Cetaceans, pinnipeds, seabirds
a) Vulnerability to OA in NZ waters	Low	Low-Med	Low-Med	?	?	Medium	?	Med-High	Med-High	?	?
b) Current knowledge in NZ waters											
Established Response to OA	Medium*+	Medium*	Med-High	-	Low	Low-Med	-	Medium*	Medium+	Low-Med*	-
Mechanistic understanding of response	Low-Med	Low-Med	Medium	-	Low	Low	-	Low-Med*	Low-Med+	Low	-
Indirect/Ecosystem interaction	Medium*+	Low-Med*	Medium*	Low	Low	Low	-	Low	Low-Med	-	-
Interaction with other stressors	Low-Med*+	Med-High*	Medium	Low	Low	Low	-	Medium	Medium+	-	-
Socio-economic/Ecosystem services	Low	Low-Med	Low-Med	Low	-	Low	-	Medium	Low-Med	-	-
Adaptive capacity	-	-	-	-	-	-	-	-	Low	-	-



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