Water & Atmosphere

November 2015

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WATER & ATMOSPHERE

November 2015

Water & Atmosphere is published by NIWA.
It is available online at www.niwa.co.nz/pubs/wa

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ISSN 1172-1014

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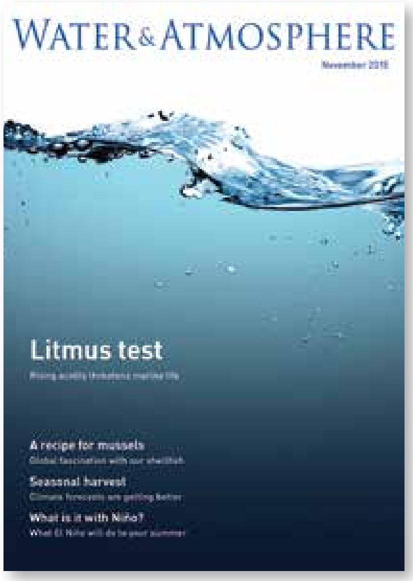


Coldest seawater discovered

A "supercoolometer", a device that sounds like it should be used to measure hipsters, has found the coldest seawater on Earth, under Antarctic sea ice.

NIWA oceanographer Dr Craig Stevens and his team are researching why, in a warming world, sea ice is growing in the Antarctic even though it is receding in the Arctic. Sea ice growth is a vital part of the climate system that influences many aspects of life on the planet. The question is, are the giant ice shelves around Antarctica responsible for this paradox?

This year the team deployed a highly sensitive instrument called a supercoolometer as well as their usual array of ocean turbulence sensors. It was developed at NIWA by Matt Walkington to look at an often ignored but possibly key part of the Earth's climate system – seawater colder than freezing point.

Dr Stevens has recently returned from a three-week field trip to Antarctica along with his team – NIWA's Brett Grant, a group from the University of Otago and the artist and communicator Gabby O'Connor. They achieved the first ever successful deployments of the supercoolometer to measure "supercool" seawater formed under ice shelves when "warm" seawater melts the ice underside.

The scientists set up their field camp on two-metre thick ice, about 25km from Scott Base, and drilled holes through the ice to reach the seawater below.

"The camp was above the very cold seawater flowing out from beneath a melting ice shelf. This water drains upwards until it reaches the edge of the shelf, where it flows out into the wider ocean.

"As it rises, the reduction in pressure elevates the freezing temperature, and so the water finds itself colder than the temperature at which it should form ice," Dr Stevens says.

At –1.94°C, this water is highly significant from a climate perspective. Dr Stevens says while it is only slightly colder than freezing, that tiny temperature change is physically huge, because ice starts to form and the ocean changes its state.

"We are looking at the possibility that the answer to why Antarctic sea ice is expanding lies in the production of this supercool seawater. It is a pathway for ice shelf water to influence sea ice growth far beyond the shelves. This is a significant issue because these shelves make up 40 per cent of the Antarctic coastline, and the Ross Ice Shelf is the size of France.

"It's also waving the flag for exploring some of the unique processes within the Earth system and finding out which of those are important."

Along with temperature, the supercoolometer measures salinity, and other sensors measure turbulence in the water and currents.

Craig Stevens removes ice crystals which have formed on the 'supercoolometer'. (*Brett Grant*)

The process comes with its own set of challenges. Water freezes on the measuring instruments within an hour of deployment. "We are developing techniques to get around that. You can make measurements, but they might be corrupted, so this is part of the scientific process to try to evaluate how reliable the measurements are."

Analysis of this latest field trip to Antarctica is already underway, and next year the team will measure the rate of melting under the ice shelves.

"This time we went through 5m of ice and platelets – in a year's time we'll go through 350m of ice. We'll be in the middle of the Ross Ice Shelf, the largest on the planet. Beneath this ice is 300m of ocean that's never been sampled before, which is pretty exciting."

NIWA's fieldwork in Antarctica, such the 'Mertz Polyna' voyage in 2013, provides vital data to help understand climate change processes. (*Helen Bostock*)

A natural history of change

Nature provides the best archiving system available, and NIWA's Dr Helen Bostock is part of an international team tapping into it to learn more about Earth's climate history during periods of abrupt change.

The history of Earth's climate is stored in tiny variations in ice, ocean sediments, peat bogs and other natural archives over thousands of years. Recovering and deciphering how and why the climate has changed in the past is providing scientists with a way to understand climate systems.

'Abrupt climate change' describes changes in climate that occur over years or decades, compared with human-caused changes that are occurring over decades and centuries.

Bostock, a NIWA marine biologist, joined fellow Kiwi scientists Dr Marcus Vandergoes and Dr Giuseppe Cortese from GNS Science as part of an international team that has documented duelling ocean and atmospheric heat transport during these periods of abrupt change.

It had previously been thought that changes in the amount of heat carried north by Atlantic Ocean currents were responsible for past periods of abrupt climate change.

Bostock and the team, which also included scientists from Denmark, Australia, the United States and France, found that changes in ocean heat transport were only part of the picture of abrupt climate change.

The scientists examined how the climate of the Southern Hemisphere behaved during a period of abrupt warming in Greenland and the North Atlantic. They compared climate records spanning Antarctic ice cores, marine sediment cores and even southern African rodent middens with climate model results. They were able to confirm previous ideas that increasing northward heat transport in the Atlantic warms the North Atlantic and Greenland at the expense of abrupt cooling in the Southern Ocean.

This concept is known as the 'bipolar ocean seesaw'.

The team's new finding is that atmospheric circulation adjusts in an effort to compensate for the change in ocean heat transport. As the ocean transports more heat northward, the atmosphere responds by transporting more heat southward.

However, the compensation is imperfect; climate changes in different locations throughout the Southern Hemisphere reflect the battle between the opposing ocean and atmospheric heat fluxes. In the low latitudes, over the continents, the atmosphere wins out, driving abrupt drying and warming and shifting the location of the monsoon systems. In the South Atlantic and Southern Oceans, New Zealand and Patagonia, the ocean wins out, driving cooling that is amplified around Antarctica by expanding sea ice.

Helen Bostock on board *Tangaroa*. (*NIWA*)

The research underlines the intimate coupling between the ocean and the atmosphere and helps to explain why past abrupt climate change unfolded so differently in different regions.

In brief

NIWA boat ramp worker Keith Nolan (right) with recreational fisher Ron Prestage and his catch of gurnard and blue cod. (*The Fishing Paper*)

Fishing for answers

Recreational fishers in the Marlborough Sounds, Tasman and Golden Bay are being approached at boat ramps in the region to provide information on their catches for a research survey.

NIWA is undertaking the survey for the Ministry for Primary Industries (MPI) to find out how many fish are being caught by recreational fishers.

Marine ecologist Niki Davey says the purpose of the survey, which began on 1 September, is to estimate the recreational catches of commonly caught fish such as snapper and blue cod.

"It is important that we get up-to-date, accurate information to enable fisheries' managers to make decisions using the best data available."

Fishers returning from the water are being asked if NIWA can measure their catches and know when and where they've been fishing and which methods they've used.

An aerial survey will also be carried out to provide a snapshot of the number of boats fishing in the areas.

"This year's El Niño raises the risk of summer drought in eastern parts of the country", says NIWA forecaster Chris Brandolino. (*Dave Allen*)

Drought could be on its way

The biggest El Niño since 1997/98 is here, and it could cost the country's economy hundreds of millions of dollars.

NIWA says the weather pattern could carry on through the summer, with average to below-average temperature and rainfall levels predicted for most parts of the country.

NIWA forecaster Chris Brandolino says this year's El Niño raises the risk of summer drought in eastern parts of both islands, as well as northern areas of the North Island.

"By many measures the current event is tracking close to the 1997/98 El Niño," he says.

The drought associated with the 1997/98 El Niño resulted in a loss of $618m, or 0.9 per cent of GDP – a figure estimated by the New Zealand Institute of Economic Research.

The El Niño pattern is also expected to produce above-average activity and severe tropical storms in the southwest Pacific.

Morehurehu South, a coastal dune lake set in sand dunes, scrub and pine plantation forestry. (*Rohan Wells*)

Northland dune lakes surveyed

NIWA scientists and Northland Regional Council staff are uncovering the mysteries of the north's prized dune lakes by using a canoe and some specialist hydro-acoustic surveying equipment.

Lakebed mapping of 25 dune lakes is being undertaken to provide bathymetry data as well as information on vegetation and sediment.

NIWA freshwater scientist Mary de Winton says that NIWA can produce a map just a few days after surveying by using a specialist service that turns hydro-acoustic files into bathymetric maps.

"Because we're not mapping for navigation purposes, these are rapid-fire surveys that get results quickly and are very visual and easy to understand," de Winton says.

Information on the volume, depth and features of the lakebed will contribute to the lakes' management and protection.

The next step will include developing rules for the management of the lakes.

Environmental Monitoring Technician Sally Gray deploys a helikite to observe layers of air pollutants in Rangiora. (*Dave Allen*)

Where there's smoke, there are air quality scientists

Data gathered from houses using woodburners are part of an air quality pilot experiment conducted by NIWA in the South Island town of Rangiora.

The experiment took place in September using temperature sensors in 14 homes, as well as 11 indoor and 6 outdoor air-quality sensors, to collect millions of data points.

NIWA is now analysing the data to determine whether different parts of Rangiora have different air quality levels and how the air quality varies from day to day.

NIWA's Dr Ian Longley says that the preliminary results have shown a variation in the amount of wood smoke across Rangiora, but what's causing that variation is not yet clear.

The results have also showed that the effectiveness of individual woodburners differs, with temperatures inside homes rising at different rates. Some homes warmed up at 2°C an hour, while others warmed up at about 10°C an hour.

Solar panels being installed at Lauder to measure the effects of atmosphere on solar energy production. (*Ben Liley*)

Solar panel sweet spot at Lauder

NIWA's Lauder research station specialises in measuring CRCs, ozone, ultraviolet levels and greenhouse gases, and is home to some of the best instruments in the world for atmospheric research.

Atmospheric scientist Ben Liley says the panels give NIWA the opportunity to collect data on solar power generated and compare it with atmospheric conditions.

The photovoltaic panels are capable of generating 18 kilowatts of electricity at their peak – almost enough to power the specialist equipment housed at Lauder.

NIWA expects to use data from the experiments to make improvements to its online SolarView tool. SolarView provides an estimate of the available solar energy at a particular address, taking into account landscape, nearby buildings and solar panel placement.

Scientific diver Crispin Middleton surrounded by panicked starry toado pufferfish at the Poor Knights Marine Reserve. (*Crispin Middleton*)

Snapped at NIWA's Excellence Awards

A day at the office for NIWA scientists can mean anything from taking a helicopter into the Southern Alps to check a weather station to diving in the ocean to monitor various natural habitats.

The opportunities provided by these exciting environments have led to an annual photographic competition for staff.

The winners for 2015 were announced at NIWA's annual Excellence Awards ceremony in October.

Scientific diver Crispin Middleton won the Our People section for a photograph he calls 'Toado Selfie'. Taken at the Poor Knights Islands Marine Reserve, it features Middleton surrounded by starry toado pufferfish.

The judges – photography professionals Ross Giblin of Fairfax Media, Gerry le Roux from Sciencelens and NIWA's Dave Allen – commented that the world would be a better place "if more selfies were this good".

A selection of the photographs in this year's Awards are shown on pages 34–39.

Q&A

The problem child

El Niño and its likely impact on the Kiwi summer is a hot topic as the holiday season approaches, so what do we know about, and what can we expect from, this troublesome climate phenomenon? NIWA Climate Scientist Dr Brett Mullan explains.

What is El Niño?

El Niño is one phase of a naturally occurring global climate cycle known as the El Niño-Southern Oscillation (ENSO).

El Niño disrupts normal weather patterns across much of the globe and can lead to intense storms in some places and droughts in others, affecting many lives and livelihoods.

ENSO's other phases are La Niña – the extreme opposite of El Niño – and neutral (neither El Niño nor La Niña).

El Niño and La Niña occur irregularly, typically every two to seven years. Their strength can vary significantly from phase to phase.

By the beginning of the Southern Hemisphere spring of 2015, ENSO had entered a particularly strong El Niño phase.

What happens during El Niño?

El Niño is characterised by the accumulation of unusually warm seawater along the Pacific coast of tropical South America and out along the equator to the dateline. At the same time, waters in the western Pacific, near Indonesia, become cooler than usual.

These changes occur because of a breakdown in the normal pattern of trade winds blowing in the low latitudes of the South Pacific Ocean.

In a normal or 'neutral' year, trade winds blow from the southeast to the northwest, pushing warmer water into the equatorial western Pacific near Indonesia. During El Niño, the trade winds weaken – or even reverse – causing warm water to accumulate in the central and eastern Pacific.

Conversely, during a La Niña phase, the normal pattern of trade winds is enhanced, pushing more warm water than normal into the equatorial western Pacific.

Climate scientists are conducting extensive research to better understand why this breakdown in trade wind patterns occurs.

What impact does it have on the weather worldwide?

Warm sea-surface temperatures are a key factor in the development of thunderstorms and cyclones, which deliver heavy rain to tropical areas. As a result, El Niño typically leads to much wetter and stormier conditions than usual in the eastern Pacific, particularly in coastal Peru and Ecuador, and much drier than normal conditions in the western Pacific.

Generally, more – and more intense – cyclones affect the southwest Pacific from Vanuatu east to French Polynesia, while fewer than normal affect Indonesia, Papua New Guinea and Australia.

The changes in sea-surface temperature also influence the circulation of air and moisture at high levels in the atmosphere, which can significantly affect the weather experienced on the ground in many other parts of the world, including New Zealand.

While every event is different and no single impact is certain, typical far-reaching effects of a strong El Niño include above average rainfall in southeastern South America, eastern equatorial Africa and the southern US, and below average rainfall in parts of Australia and India.

How does El Niño affect New Zealand?

Although El Niño has an important influence on New Zealand's climate, it accounts for less than 25 percent of the year-to year variance in seasonal rainfall and temperature at most locations. Nevertheless, its effects can be significant.

We typically experience stronger or more frequent winds from the west in summer, leading to an elevated risk of drier-than-normal conditions in east coast areas and more rain than normal in the west – due to the barrier effect of the Southern Alps and main North Island ranges.

In winter, colder southerly winds tend to prevail, while in spring and autumn, southwesterlies tend to be stronger or more frequent, bringing a mix of the summer and winter effects.

During particularly strong El Niño phases, these effects can be more intense.

NIWA climate scientists have used past strong El Niño phases to approximate what may happen during the summer of 2015/16. In 1982/83 and 1997/98, the last two very strong El Niño events, severe drought occurred in some eastern parts of the country.

While east coast drought is not a certainty during every El Niño, and the districts in which drought occurs can vary from one El Niño to another, the risk is sufficiently elevated this summer to warrant risk-management actions

During El Niño we typically experience stronger or more frequent winds from the west in summer, leading to an elevated risk of drier-than-normal conditions in east coast areas and more rain than normal in the west. (*Dave Allen*)

by farmers and others whose livelihoods are likely to be adversely affected by prolonged dry conditions.

Does El Niño affect just the weather?

El Niño's effects were first noticed as early as the 1600s, by fishermen working off the Pacific coast of tropical South America. The accumulation of warmer-than-normal surface seawater in the area during El Niño suppresses the upwelling of nutrient-rich cooler water from below. As a result, fish catches are significantly reduced, due to the lack of available nutrients to sustain the marine food web.

The fishermen coined the term El Niño – Spanish for 'the little boy' or 'the Christ child' – because the effects on their livelihood were most noticeable around Christmas time. La Niña translates as 'the little girl' – the opposite of El Niño.

El Niño disrupts normal patterns of marine life and ocean currents throughout the Pacific Ocean.

When will things get back to normal?

Each ENSO phase usually lasts between nine and 12 months. Typically El Niño strengthens towards the end of year, then steadily weakens, so we can expect neutral conditions to return towards the middle of 2016.

Will climate change make El Niño episodes more common and intense?

Some climate researchers have suggested the frequency and intensity of El Niño and La Niña phases will be affected by climate change. However, there is no scientific consensus on this issue, or on whether the relatively high frequency of El Niños observed over the last two decades is related to the rise in global temperatures this century.

Climate change is likely to increase the frequency and intensity of extreme weather events, such as floods and droughts, regardless of whether they are associated with El Niño.

(Darryl Torckler)

Collaborating to meet a global challenge

It is timely that the nation is turning to confront the threat of ocean acidification. The pH of the world's oceans is falling in relation to the increase in atmospheric carbon dioxide because the oceans absorb more than a quarter of that CO_2. Around the world there is mounting concern about the impacts that future pH levels are likely to have on survival and growth of shellfish and other marine organisms.

New Zealand's answer is a model of cooperation and foresight across central and local government agencies, the fishing industry, the scientific community, iwi and other community representatives. Like the Government's National Science Challenges, it is a model of the 'best team' approach – when organisations pool talent and resources to find solutions to national, or global, issues.

The aquaculture sector has set a target of $1 billion in export earnings by 2025. One key to achieving this ambitious target is the commercialisation of high-value finfish to complement New Zealand's magnificent salmon aquaculture, and we at NIWA have made huge progress towards such success with kingfish and h?puku at our Northland Marine Research Centre at Bream Bay.

Some of the aquaculture sector's growth target, however, is expected to come from the current shellfish mainstays of the sector – mussels and oysters – but ocean acidification, and other environmental changes such as increasing sea temperatures, will challenge the achievement of that goal. The early pioneers in ocean pH studies now seem extraordinarily prescient. Ocean pH is now falling faster than any time in the past 250 years – during which it has already fallen by 26%.

The Government has put almost $5 million into a four year research project to assess this threat. It's an investment which could well help the industry realise the $1 billion goal.

The project, dubbed CARIM (Coastal Acidification: Rate, Impacts and Management), is a world-first because it will study the link between real-world changes in ocean pH and actual changes in marine species. It will ascertain the extent of the changes acidification will cause, and identify ways we can adapt our aquaculture.

The project involves a series of field and lab experiments, connected with constant measurements of pH levels at up to a dozen coastal locations.

Whilst this is a NIWA-led project, we are collaborating with scientists from other organisations, and we are working directly with the shellfish sector and community representatives. The industry is, for example, running some of the monitoring stations.

Underlining the foresight of the CARIM project is that it has connected and enlarged a fragmented assortment of unique scientific projects. NIWA scientist Kim Currie, for example, has been monitoring pH in the waters off Otago for 17 years. Over time, she has been joined by shellfish farmers and others to form a small network of monitoring stations.

The shellfish farmers want to know what's happening, and they want to know how quickly it is happening – that information will be fundamental in helping them grow their industry.

CARIM is an illustration of cooperation, optimism and smart science. It is an excellent example of what is required to help New Zealand's primary industries successfully adapt to the environmental changes we will face over the coming decades.

I will be watching the results eagerly – they have huge ramifications for our industry and fishing culture in New Zealand, and for the rest of the world.

John Morgan is Chief Executive of NIWA.

Putting the acid on

The world's oceans are acidifying as a result of the carbon dioxide (CO_2) generated by humanity.

(Dave Allen)

Putting the acid on

A report by the United Nations Convention on Biological Diversity last year noted that the ocean's pH, a measure of acidity, had decreased by 26 per cent since the start of the industrial revolution, mirroring the proportion of manmade CO_2 emissions that the oceans absorb from the air.

Globally the oceans' average pH is currently 8.1, which is 0.1 lower than it was 250 years ago. That may not sound significant, but the pH scale is logarithmic, so a decrease of one pH unit represents a 10-fold increase in the acidity. What's worse, this decline in pH is projected to continue in line with the increase in atmospheric CO_2, leading to the most rapid decrease in ocean pH in the past 50 million years.

Ocean acidification, as this process is known, has happened before. CO_2 from Siberian volcanoes caused the world's oceans to acidify 252 million years ago, generating the greatest-ever extinction of life on this planet.

A study published in *Science* earlier this year, led by Matthew Clarkson, a geochemist at the University of Otago, showed that the initial land-based extinction was followed by a second wave of marine extinction as ocean pH levels dropped by about 0.7 units.

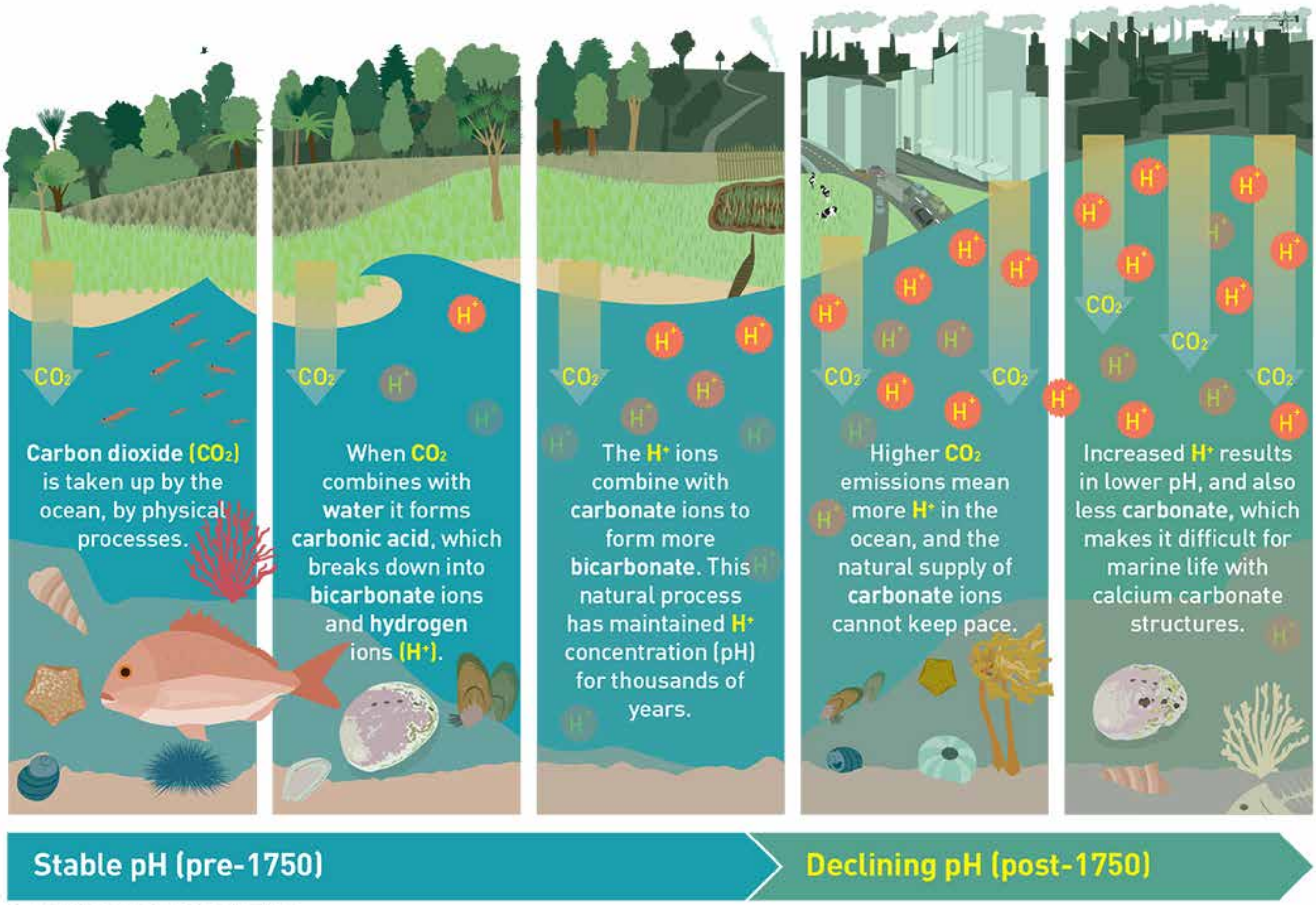
This ancient calamity in the Permian era suggests that there is much at risk from a new onset of ocean acidification. Studies of global and New Zealand marine organisms suggest there will be a number of impacts, from the coast to the deep ocean. For example, NIWA scientists estimate that perhaps 25 per cent or less of the existing cold water coral locations around New Zealand will be able to sustain their growth by 2100 because of ocean acidification.

New Zealanders may also be more directly affected by ocean acidification. For example, shellfish aquaculture on the western coast of the United States has already been affected by reduced larval survival and weaker shells as a result of lower ocean pH.

Just this month the Minister for Primary Industries, Nathan Guy, launched a study by the New Zealand Institute of Economic Research, which showed that $276 million in annual export earnings and 859 jobs are generated from aquaculture in Marlborough. To protect this industry, and the vulnerable marine ecosystems on which it relies, the New Zealand Government has funded a four-year research programme that includes cutting-edge monitoring and field experiments to identify how rapidly our coastal waters are acidifying and the likely effects on marine life.

Marine biogeochemist Cliff Law at NIWA's Wellington ocean acidification facility. (*Dave Allen*)

The chemistry of acidification – how increasing CO_2 leads to ocean acidification



Source: NIWA. Graphic: Nicky Barton/Arie Ketel

Chemical brothers

The uptake of CO_2 by the ocean is regulated by physical processes such as waves and temperature.

When CO_2 is combined with water it forms H_2CO_3 (carbonic acid). H_2CO_3 breaks down rapidly into HCO_3^- (bicarbonate) and H+ (hydrogen ions).

The H+ ions combine with carbonate in seawater to form bicarbonate. This natural process has maintained the H+ ion concentration (and therefore the pH) of the ocean for thousands of years.

However, increasing CO_2 emissions cause CO_2 to enter the ocean at a faster rate, and the natural supply of carbonate (from coastal regions and the deep ocean) cannot keep pace. As a result there is an excess of H+ ions, and pH and carbonate are decreasing.

The resulting decrease in carbonate availability makes it difficult for many marine animals to maintain their calcium carbonate shells.

Slow dawn

Dr Cliff Law, NIWA's Principal Scientist, Marine Biogeochemistry, says that a decade ago the focus on the effects of CO_2 on climate masked the risks posed to the oceans.

"Back then scientists were interested in the oceans as a sink for CO_2. Oceans were a key player in the models – absorbing a lot of humanity's carbon emissions.

"However, scientists started wondering about the effects of the extra carbon. We understand the oceans' chemical dynamics, so it was a straightforward calculation to work out that adding more CO_2 would lower the pH." (See graphic, The chemistry of acidification.)

Scientists started looking for evidence of falling pH, but detecting the small year-by-year changes was difficult, requiring sensitive equipment and long-term monitoring to show clear trends. However, acidification is now apparent, with several time-series stations around the globe showing long-term trends of decreasing pH. For example, the pH at the Hawaii Ocean Time-series has fallen from 8.12 to 8.07 in the past 25 years.

Putting the acid on

It's the same story elsewhere. Studies off the US west coast, a region critical to the oyster industry that experiences naturally low pH, recorded a decline in pH that has been linked to high larval mortalities in hatcheries.

A 2015 study by Oregon State University found that more than 80 per cent of respondents from the US's west coast shellfish industry were convinced that acidification was having consequences, with 50 per cent of the industry reporting they had already experienced some impacts from acidification.

One operator, the Hog Island Oyster Company, has found that oysters brought in as juveniles from Oregon and Washington, grew less reliably and more slowly and had a higher mortality rate than they had several years earlier.

New Zealand is not immune to ocean acidification. The 'Munida transect' time-series in sub-antarctic waters off Otago is the Southern Hemisphere's longest-running record of pH measurements. Monitoring since 1998 has established a decline in pH that reflects the increase in atmospheric CO_2 recorded at NIWA's atmospheric research station near Wellington.

The Munida time-series is led by NIWA's Dr Kim Currie, in collaboration with the University of Otago's Department of Chemistry. Every two months she has collected water samples along a 65-kilometre line from the tip of Otago Harbour out to sub-antarctic waters. This time-series is particularly valuable because it covers both subtropical and sub-antarctic waters in a one-day trip, so is in a unique location.

During the transect University of Otago scientists measure the pH while Currie measures alkalinity, total dissolved inorganic carbon and CO_2 as well as other related parameters. The supporting data help to determine what processes are causing changes in the properties of the water masses, including the changes in pH. For example, pH is linked to temperature and therefore varies between summer and winter and also year to year.

Currie refers to the time-series as "sentinel monitoring".

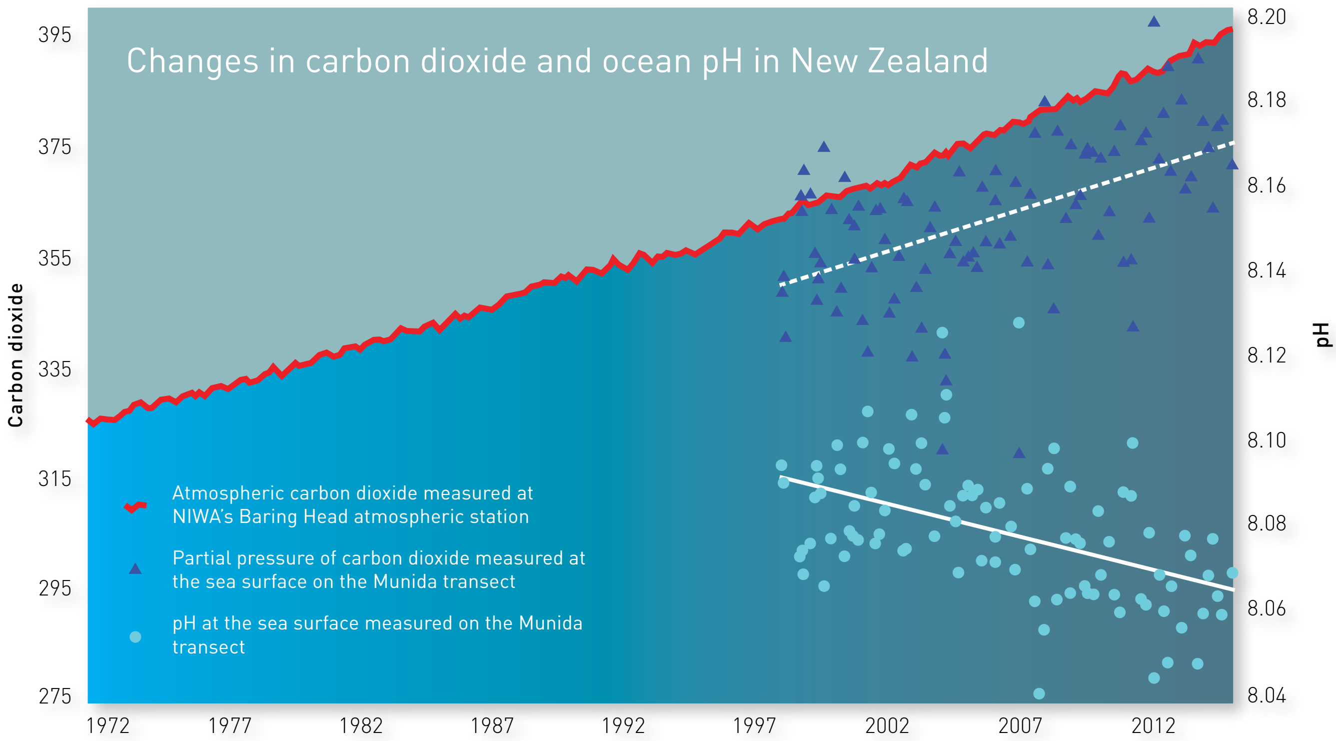
"We have been taking regular samples in the open ocean for 17 years. The open ocean is less likely than coastal waters to be influenced by localised or short-term anomalies – so when we see change in the open ocean, we know something significant is going on.

"In fact it took over a decade before the series could discern a long-term change in pH from the natural variability."

Close to home

Kim Currie is not the only one concerned by the acidification issue. She found many willing partners when she sought to set up a nationwide network of stations to monitor coastal pH.

The New Zealand Ocean Acidification Observing Network (NZOA-ON) comprises 14 pristine and urban monitoring sites around our shores.



In true Kiwi style the network is actually the coordination of a wide range of sampling partners. It uses existing data collection infrastructures where possible, for example three NIWA sites, two sites monitored by regional councils, and a site on Stewart Island monitored by the Department of Conservation.

It has been expanded to include others, such as a pāua operation in the Chatham Islands and a fishing company on the West Coast, which have agreed to take samples at the location of their operations.

The NZOA-ON sampling partners collect water samples, liaise on shipment and logistics, and assist with the deployment of the sensors. Fortnightly water samples from each site are sent to NIWA's Dunedin laboratory for the analysis of ocean acidification parameters – alkalinity and total dissolved inorganic carbon – which allow the calculation of pH and carbonate availability. pH sensors are also deployed for four or five months at each site on a rotating schedule, to measure the short-term pH variability at each location.

Data gathered from sampling are used to determine local conditions and to provide a baseline against which to assess future change. The network is linked to the Global Ocean Acidification Observing Network, an international initiative led by the National Oceanic and Atmospheric Administration (NOAA) in the US, which coordinates global monitoring.

Currie says a decade of data may be needed to assess reliably the variability of coastal pH and whether the level is changing.

"The first two years will give us a baseline picture of the variations in pH of our coastal waters, but we'll need longer to know whether it's declining," she says.

What's the worry?

There is no information on public awareness of the problem in New Zealand, but international studies show only low levels of alarm. Oregon State University estimated the public awareness of acidification and its impacts at about 20 per cent, compared with widespread awareness from those involved in the commercial fishing industry.

A 2014 United Kingdom study also found that only 20 per cent of the public had ever heard of ocean acidification.

In New Zealand, Anna Crosbie, Senior Aquaculture Analyst at the Ministry for Primary Industries, says that at the moment ocean acidification is not affecting the domestic aquaculture industry.

"However, it is important that we learn the lessons from other ocean acidification events around the globe, and improve our understanding of adaptive measures we can take to improve our long-term resilience to changing ocean chemistry."

Kim Currie (right) taking water samples on board RV *Polaris* with a chemistry student. (*Dave Allen*)

Mary Sewell, Associate Professor of Biology at the University of Auckland, says ocean acidification has the potential to affect food security and other ecosystem services that are provided by the oceans.

Miles Lamare, from the University of Otago's Department of Marine Science, says laboratory experiments have already shown that abalone, including New Zealand pāua, can be harmed by reduced seawater pH.

The effects are seen at all stages in the lifecycle, such as larvae not being able to grow shells or develop normally, and juveniles having reduced growth, thinner and eroded shells, and reduced survival rates.

Operators in the New Zealand pāua industry are worried that they are seeing the first signs of decreasing pH in the seas around New Zealand.

Jeremy Cooper, Chief Executive of the Pāua Industry Council, believes it's only a matter of time before the industry has to face up to major problems.

"Our divers are working at the coalface and are completely in tune with reality. Many people think it will be the next generation's problem, but we know this is not the case because divers are seeing changing ecosystems. When pāua shells and other shellfish begin dissolving in the water we will know we have a real problem."

Lessons have already been learned from the Whiskey Creek Shellfish Hatchery in Oregon, US. Its operators discovered that seawater of lower pH inhibited shell growth, and oyster larvae were not surviving beyond 48 hours. The larvae were simply unable to form the first layer of calcium carbonate needed for survival.

Marine biologist Graeme Moss (left) and Principal Technician Neill Barr at NIWA's newly completed ocean acidification facility at Greta Point, Wellington. The facility will be used to examine the effects of combinations of pH and temperature on different life stages of pāua. (*Dave Allen*)

Cooper points to NIWA research that suggests pāua will likely suffer the same fate if ocean acidification continues.

"For our industry, if juvenile pāua do not survive, the fisheries' replenishment pathways will be completely disrupted and the resource will begin a downward spiral. If this happens it will be only a matter of time before pāua essentially becomes a mined resource, unable to replenish itself."

Nascent science

Scientists are now working with stakeholders from industry, ministries, regional councils, the Department of Conservation, and iwi partners to combine resources to tackle coastal acidification under one banner – a four-year programme funded with $4.9 million from the Ministry of Business, Innovation and Employment (MBIE).

This project, dubbed CARIM (Coastal Acidification: Rate, Impacts and Management), is coordinated and led by NIWA and is designed to establish the scale of acidification and how it is affecting New Zealand coastal ecosystems. It effectively knits together existing frameworks with new research directions and collaborations to enable scientific breakthroughs into the impacts and mitigation of coastal acidification.

Dr Rob Murdoch, NIWA's General Manager of Research, says ocean acidification is particularly concerning in coastal regions where New Zealanders access most seafood, and where reductions in pH can be made worse by land runoff.

Cliff Law, the CARIM programme leader, says pH monitoring will take place at the Firth of Thames, Karitane and Nelson Bays – three locations that are important for iconic species including Greenshell™ mussels, pāua and snapper, which are ecologically, economically and culturally important in New Zealand.

"We will determine the sensitivity of their different life stages to lower pH, and also whether associated changes in food quality, availability and habitat will affect their survival. We will also examine the potential for shellfish to adapt to acidification – just one of the tools and approaches that may mitigate the impacts."

After years of small and disparate scientific efforts, Kim Currie is delighted.

"The study of ocean acidification is finally starting to take off in New Zealand. The previously uncoordinated monitoring and independent impact studies are now coalescing into a unified effort."

Where and how much?

Law says MBIE is enabling the first coherent, 'end-to-end' project on ocean acidification.

"The separate components within CARIM are interlinked: we're measuring the pH changes, the causes and the impacts on marine life, and identifying how to respond.

"The overall result will be better models, allowing more accurate predictions of the impacts of acidification in coastal waters, and providing management options for stakeholders."

Law is particularly pleased with the focus on the measurement of coastal pH levels.

"Coastal waters are the most variable in their natural pH levels; they are where we get the most benefits in terms of food, recreation and other amenities, yet also where we affect the ocean most."

The data will help to fine-tune models of pH in coastal waters, and also shellfish population models. They will also give clues as to how to use the natural resilience of shellfish to adapt, which may benefit aquaculture.

The Firth of Thames study will use nutrient, current and river flow data in dynamic models to assess the relative contributions of the atmosphere, land and ocean to changes in pH, informing management options for reducing the impacts of land-based activities on coastal pH.

Pinpointing plankton

Law will coordinate research into the impacts of acidification on phytoplankton during CARIM.

At NIWA's Wellington site a number of 4000-litre tubes – known as 'mesocosms' – will be filled with surface water from Wellington Harbour. The objective is to see how plankton in the water respond to the changes in temperature and pH that are projected for this region in the future.

Permeable tubing regulates the diffusion of CO_2 into water in the mesocosms under the control of an automated feedback system, allowing the researchers to set pH and temperatures to future levels.

"Plankton are responsible for at least half of the oceans' CO_2 uptake, so they help to regulate climate. Just as importantly they form the base of the marine food web. Understanding their response to acidification is critical to both climate models and the future productivity of our fisheries and ecosystems."

In one of the buildings near the mesocosms, another CARIM experiment will look at the sensitivity of pāua to temperature and pH. This world-class facility consists of rows of pāua-filled aquariums festooned with equipment to control and monitor their watery environment.

These experiments, coordinated by NIWA's Dr Vonda Cummings, are examining the effects of combinations of pH and temperature on different life stages of pāua – particularly the settlement of the larvae and mortality rates, where problems have been observed in other parts of the world.

In combination with a Ministry for Primary Industries project, and in collaboration with Australian scientists, CARIM is also examining the effects of lower pH on snapper larvae.

International studies have shown that low pH affects the sensory behaviour of fish, causing them to lose their sense of smell, wander farther from safety and lose the capacity for predator recognition. These impacts may have big implications for snapper survival, and the studies to be carried out by Darren Stevens at NIWA's Northland Marine Research Centre at Bream Bay are important to establish the future prospects of one of the nation's favourite fish.

Make them stronger

Until now the impacts of falling pH have been mainly theoretical and laboratory based.

The University of Otago's Miles Lamare says we cannot know the effects of falling pH until we extrapolate the laboratory findings to the real world.

"Ocean acidification will coincide with a number of other key environmental changes, such as ocean warming and coastal degradation," says Lamare.

"Laboratory experiments probably don't realistically replicate the variability that occurs in the natural world, both in time and between habitats. Nor have short-term laboratory experiments been able to take into account the capacity of marine species to adapt and acclimate to pH changes."

Lamare's own experiment will look at settlement from the plankton onto the seafloor, a key stage in the lifecycles of marine invertebrates like mussels and pāua.

A vital part of the kit for measuring ocean acidification, the CTD (Conductivity, Temperature, Depth) profiler is lowered to different depths throughout the water column to capture samples and valuable data. (*Dave Allen*)

"Settlement involves specific cues that ensure animals settle in suitable locations, so we need to understand if this process is affected by ocean acidification.

"We will be growing suitable substrates under different future ocean acidification scenarios, and will examine how settlement behaviour changes. To understand patterns in settlement under realistic ocean acidification scenarios, we will quantify the changes in substrates by examining differences in the microbial community and biofilms.

"We will rear larvae under the same pH conditions to explore whether changes in settlement can be a result of changes in larval development, sensory capacity and behaviour. For example, larvae seem to develop more slowly in low pH. Work on other invertebrate larvae suggest they become less selective about where they settle if their development is slower than normal."

Lamare also hopes to explore the processes in a range of marine invertebrates to see if these issues are species specific or general, and if mussels and pāua are more or less sensitive at the settlement stage. This would be essential information for a shellfish industry considering its future farming stock.

At the end of the four years, says Lamare, the lab and field studies will be incorporated into pāua population models, and data on natural variability in the coastal pH environment will help to create more accurate lab experiments.

Norman Ragg, of the Cawthron Institute, leads the CARIM experiments looking at physiological differences between mussels that are resilient and those that are susceptible to acidification.

"Our initial task is to place sentinel mussels at the three sites where pH is being monitored. These will be babies straight out of the hatchery, around the size of a grain of rice, which will act as bio-sensors.

"During year one of the project we will create a single ocean acidification scenario or environment in the laboratory using NIWA projections. We will then monitor 40–80 new families and examine how they respond to these conditions. The aim is to determine vulnerability in the different life stages, and identify those families showing more resilience or susceptibility."

Ragg says the most resilient mussel families could be a great commercial tool for an acidified future.

"By year two we want to be able to identify the special biological material in the families at the extreme ends of the scale. What is it that brings resilience into the species at a biological level? Are the mothers' experiences, such as exposure to low pH, conferring benefits? If so, does this show up in the young as resilience?"

He says there is certainly no clear evidence of mussels being affected by ocean acidification at this stage.

"It's important to clarify the difference between ocean acidification and coastal acidification. CO_2 from the air is not the only contributor to coastal acidification.

"At this stage we have little understanding of how local inputs such as river flow, local land use such as forestry and nutrient runoff might be affecting our coastal waters – and the places we are farming mussels."

Ragg says the variables in the processes make for complex science.

"Nitrate runoff from fertilisers contributes to algae growth, which is good for mussels. On the other hand, when the algae start dying off in late summer and autumn, the associated decomposition could increase CO_2 and decrease the pH in water bodies like the Firth of Thames."

The University of Auckland's Mary Sewell is working with Cawthron on the impacts of ocean acidification on the early development of mussels.

"We are measuring changes in gene expression, protein expression and small chemical molecules to identify biomarkers of coastal acidification stress.

"This will allow us to understand better the biological functions that are being affected by ocean acidification and the potential impacts that this might have in the coastal marine ecosystem."

A major benefit of the CARIM project is that monitoring of shellfish can be matched to the monitoring of coastal pH on a daily and seasonal basis, and also spatially at the sentinel sites.

"This will provide a huge leap forward in understanding how ocean acidification will affect New Zealand's coastal marine ecosystems," Sewell says.

"We can design our experiments to measure the responses of mussels and pāua to ocean acidification in current and future conditions, then use these results in predictive models."

The experiments will provide clues to the impacts of ocean acidification in uniquely New Zealand conditions – such as on aquaculture in shallow embayments where there is sometimes significant nutrient runoff from land. In these areas the combination of increased atmospheric CO_2 and coastal nutrient enrichment can result in a very-low-pH environment.

"New Zealand needs to understand these in detail, so that we can develop strategies to mitigate the effects of ocean acidification."

Soluble solutions

While one thread of the CARIM project measures the extent and impacts of acidification, the other will be drawing lessons on adaptations and solutions.

Jeremy Cooper says if the effects of ocean acidification on pāua become real, pāua businesses may become more like farming operations, hatching larvae in controlled conditions and allowing them to strengthen their shells before reseeding them into the ocean.

"We need to leapfrog Mother Nature's bottleneck. Instead of worrying, we need to identify the problems and work with them.

"It's highly likely that ocean acidification will affect different parts of the coastline at different rates. If we can identify areas of ocean around New Zealand where ocean acidification is not having as great an effect, we could target these areas for enhancement to maximise overall productivity."

He thinks the solution also requires a wider view of the inputs and outputs, to see where humanity can help alter conditions.

"Mussel shells are largely made up of calcium carbonate, but every year tonnes and tonnes of their calcium carbonate shells are being pulled out of the ocean and end up in landfills. This could be compounding the problem. In other countries around the world they have to return shellfish shells to the ocean to help replenish the micro and macro nutrients in the water column. Perhaps we need to be looking at this as well."

Miles Lamare is hopeful that CARIM will provide more information about the capacity of coastal species to adapt to a changing environment.

"With good information, worry about ocean acidification might be replaced with the positive management of any issues.

"We may be able to implement strategies that mitigate future problems. For example, we could decide to pursue farming resilient strains of mussels, or restoring resilience to changes in coastal ecosystems by improving coastal health."

Cliff Law says the jury is out on how we can adapt our use of the ocean to acidification, but New Zealand is about to make a valuable contribution to the emerging acidification science.

"The CARIM project will provide more coherent models that include both direct and indirect ecosystem effects to obtain a clearer picture of how coastal acidification will affect these iconic species, and how we can manage those effects."

Every three years ocean acidification scientists converge for the International Symposium on the Ocean in a High CO_2 World. When it is held next May in Tasmania, Law will be explaining the plans and progress of the CARIM project.

After at first failing to appreciate the effects of CO_2 on oceans, the world has a lot of catching up to do.

Seeing is believing

A 2015 US survey by Oregon State University found that more than 80 per cent of respondents from the West Coast shellfish industry were convinced that acidification was already having consequences.

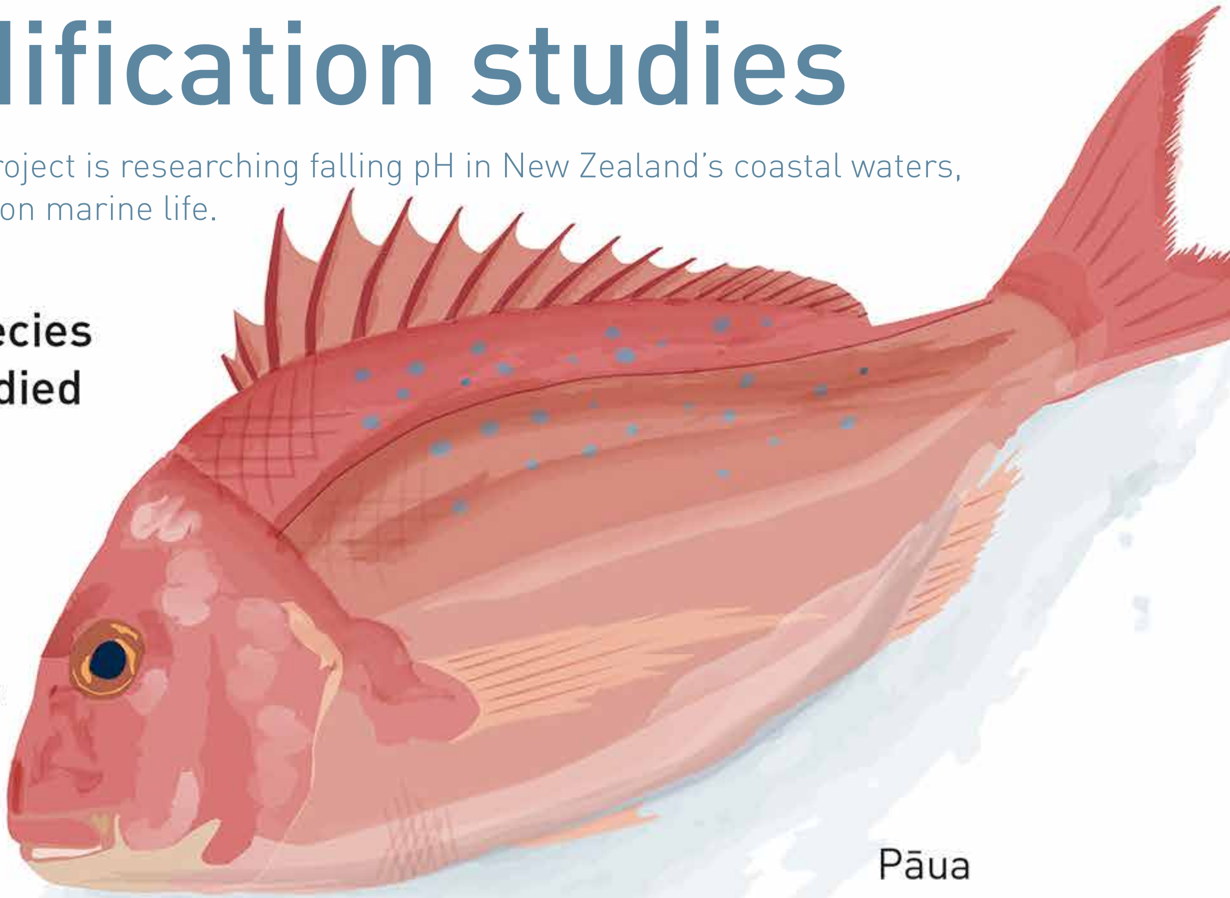
About half of the respondents reported experiencing the impacts in their work, with 97 per cent saying ocean acidification had caused them financial damage.

Rebecca Mabardy, the lead author on the study, says the shellfish industry recognised the consequences to a far greater extent than the public.

Marine ecologists at Oregon State University have noted that many shellfish farmers have seen the effects of acidified water on the survival of juvenile oysters. But some early success in hatcheries' adaptation to changing conditions has generated guarded optimism that the industry can adapt.

Acidification studies

The CARIM project is researching falling pH in New Zealand's coastal waters, and its effect on marine life.

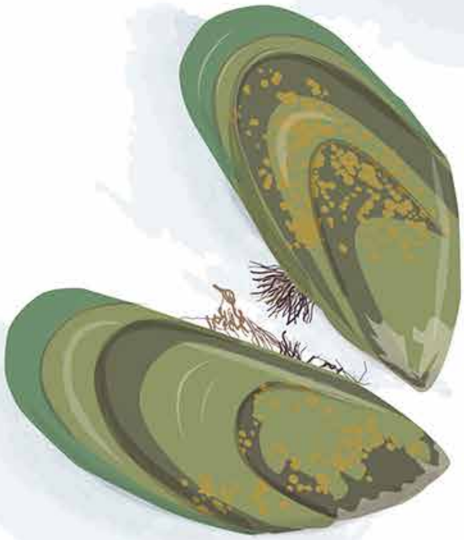


Iconic species being studied

Snapper

Snapper larvae will be tested at NIWA's Northland Marine Research Centre at Bream Bay.

International studies have shown that changes to pH affect the sensory behaviour of fish, causing them to lose their sense of smell, affecting their learning and hearing and reducing predator recognition.



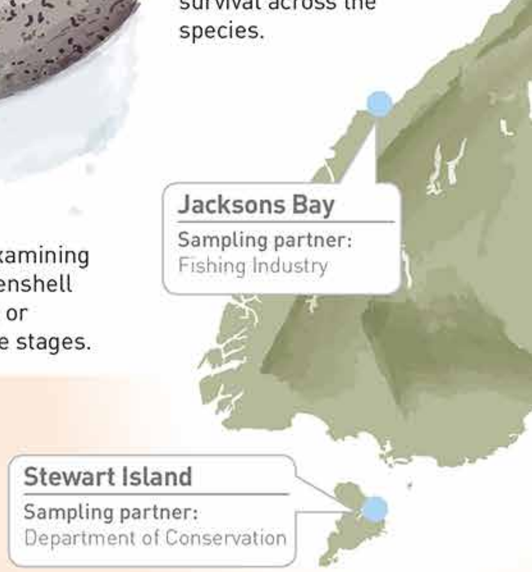
Pāua

Laboratory experiments have already shown that pāua can be harmed by reduced pH in seawater.

The effects cross all stages in the lifecycle, with larvae unable to grow, juvenile shells eroding and reduced survival across the species.

Greenshell mussels

Scientists at the Cawthron Institute are examining whether genetic differences between greenshell mussel families influence their resilience or susceptibility to acidification at various life stages.



Source: NIWA www.niwa.co.nz. Graphic: Nicky Barton/Arie Ketel

Experiments

Will the composition and food quality of plankton alter under future conditions?

Using 4000-litre bags, known as "mesocosms", at NIWA's Wellington site, scientists will determine coastal plankton's response to changes in temperature and pH, to understand the effects further up the food chain.

How will larval settlement be affected?

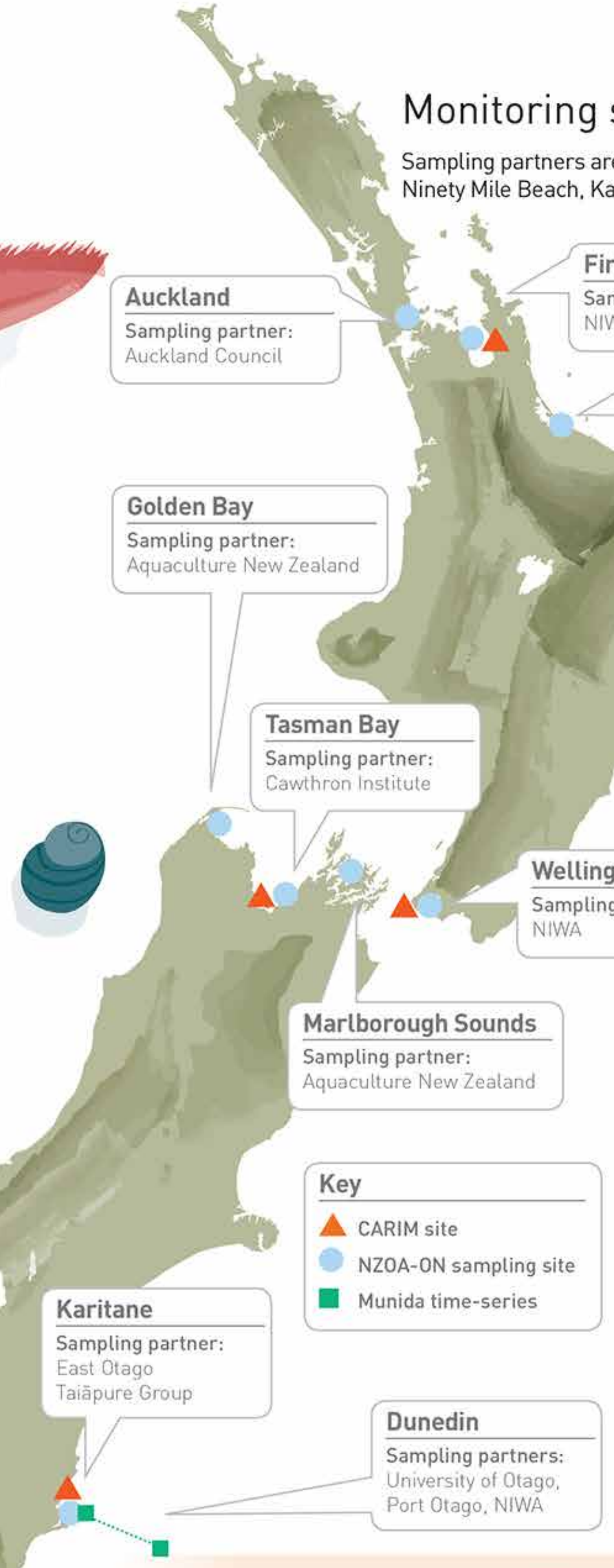
Coralline algae provide a substrate for pāua larval settlement on the seafloor. University of Otago and NIWA scientists will determine how larval settlement success varies for larvae and coralline algae grown under different future ocean acidification scenarios.

Are snapper larvae affected by ocean acidification?

NIWA scientists will use the Bream Bay facility to test whether the behaviour of snapper larvae changes in response to lower pH.

Monitoring sites

Sampling partners are being sought for Ninety Mile Beach, Kaikoura and Bluff.

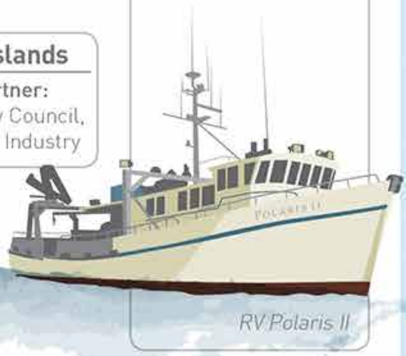


Long-term sampling

The Munida CO_2 time-series transect has been measuring hydrographic, nutrient, carbonate system parameters and air-sea CO_2 exchange data since 1998.

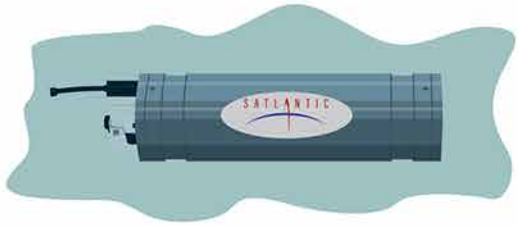
Every two months, water samples are collected along a 65-kilometre line from the tip of Otago Harbour out into subantarctic waters.

Results show the waters are acidifying.



RV Polaris II

pH sensors



How do we measure pH?

The CARIM project and NZOA-ON are using SeaFET sensors to measure the pH of seawater.

The sensors are deployed on moorings or metal frames and scientists are able to set them to measure pH at any time frequency.

Every three months, the sensors are collected and taken back to the lab to download data before being returned to the sea.

Can shellfish adapt to ocean acidification?

The Cawthron Institute and NIWA will compare the response of a number of different families of pāua and green-shell mussels exposed to lower pH, to identify which are the most and least vulnerable.

Which life history stage is the bottleneck?

Using special aquariums, NIWA and University of Otago scientists will carry out experiments on pāua larvae, juveniles and adults to determine which life-history stage is most vulnerable to ocean acidification.

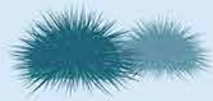
They will also determine the relative success of larvae from parents that have been exposed to low pH, to see if preconditioning to low pH can improve survival.

Other species

Pteropods

Experiments have already shown that pteropod shells dissolve in carbonate levels projected for 2050.

Sea urchins



The larvae of sea urchin species from tropical to Antarctic waters show malformation under low pH.

Red algae

Some species of seaweed may grow better under more acidic conditions.

Seaweeds

The community structure in seaweeds in coastal regions may be altered in response to ocean acidification.

Cold water corals

These require carbonate for their exoskeletons. Estimates suggest that only 25% of the current locations where cold water corals are found may have sufficient carbonate by 2100.

Whales

Top consumers in food webs, such as whales, may be affected by changes in plankton.

Mussel power

The seafood counter at your local supermarket has changed.

[istockphoto]

You might have noticed – it's got bigger, there's a lot more variety, a constant supply and hardly anything pre-packaged.

It's changed because you've changed.

You go to the supermarket more often, you're more likely to pick up a basket than push a trolley, and you want your goods super fresh in quantities that you can specify. You welcome ideas on what to make for dinner, especially if it comes with cooking advice.

And you're eating more seafood than ever, says David Jose.

He is the seafood manager at Foodstuffs, the company that runs New World and Pak'nSave supermarkets.

More people eating more seafood, he says, can be attributed to three things. Firstly, there's those changing shopping habits, then there's the enduring marriage between television and cooking competition shows.

"*Masterchef* and *Our Kitchen Rules* are in your face, showing you how to cook. The competitors use seafood quite often and they show you that it's pretty easy, that it's healthy and good for you and looks trendy at the same time. That's where the biggest change has come from."

The third factor is New Zealand's evolving ethnicity. Jose says Asians, in particular, view seafood as their main protein, in the same way we have traditionally viewed red meat.

Live mussels are a huge part of that, particularly at Pak'nSave. While many people traditionally regarded them as a snack, Jose says mussels are now more often bought by the kilo, sometimes up to three or four kilos at a time.

That means that getting them through the supply chain quickly is crucial, as is consistency.

Foodstuffs NZ seafood manager David Jose. (*Foodstuffs*)

"We're very spoilt here. We can collect seafood at the beach and we expect to buy product as good as those we collect ourselves. We want the best, as fresh as we can possibly get."

This season, as it happens, mussels are better than ever.

Mussel farmer Graeme Clarke says it's been "20 odd years or more" since he's seen mussels as big as the ones he's harvesting in the Marlborough Sounds this year.

"It's amazing, the growth rate has been incredible."

Fellow farmer John Young agrees: "I haven't seen mussels this fat in a long time. We're having a wonderfully productive season, it's phenomenal."

The wet spring and plenty of nor'west winds have been good to mussel farmers in the Sounds. It's brought more food for their crop to help boost growing conditions. El Niño, the weather pattern that brings the threat of drought to eastern areas, and this year is being compared to the horror drought of 1997–98, is, ironically, a welcome visitor here.

Commercial mussel farming began in New Zealand in the late 1970s and expanded rapidly over the next decade. Today, there are almost 700 mussel farms operating, most of them in Marlborough. It is a multi-million dollar export business that underpins the ambitious plan of Aquaculture New Zealand to achieve $1 billion in overseas sales for the sector by 2025.

But it is also an industry that continues to face fluctuating harvests and a raft of environmental issues that need a combination of science, ingenuity, cooperation and courage to address.

John Young is a strong advocate of the need for science in the mussel industry. He has farmed in the Marlborough Sounds for more than 40 years and ridden the waves of prosperity and heartbreak, misinformation and bias that have come with the territory.

"What I do know is that as a farmer you've got to move quickly when something isn't right, otherwise you go broke."

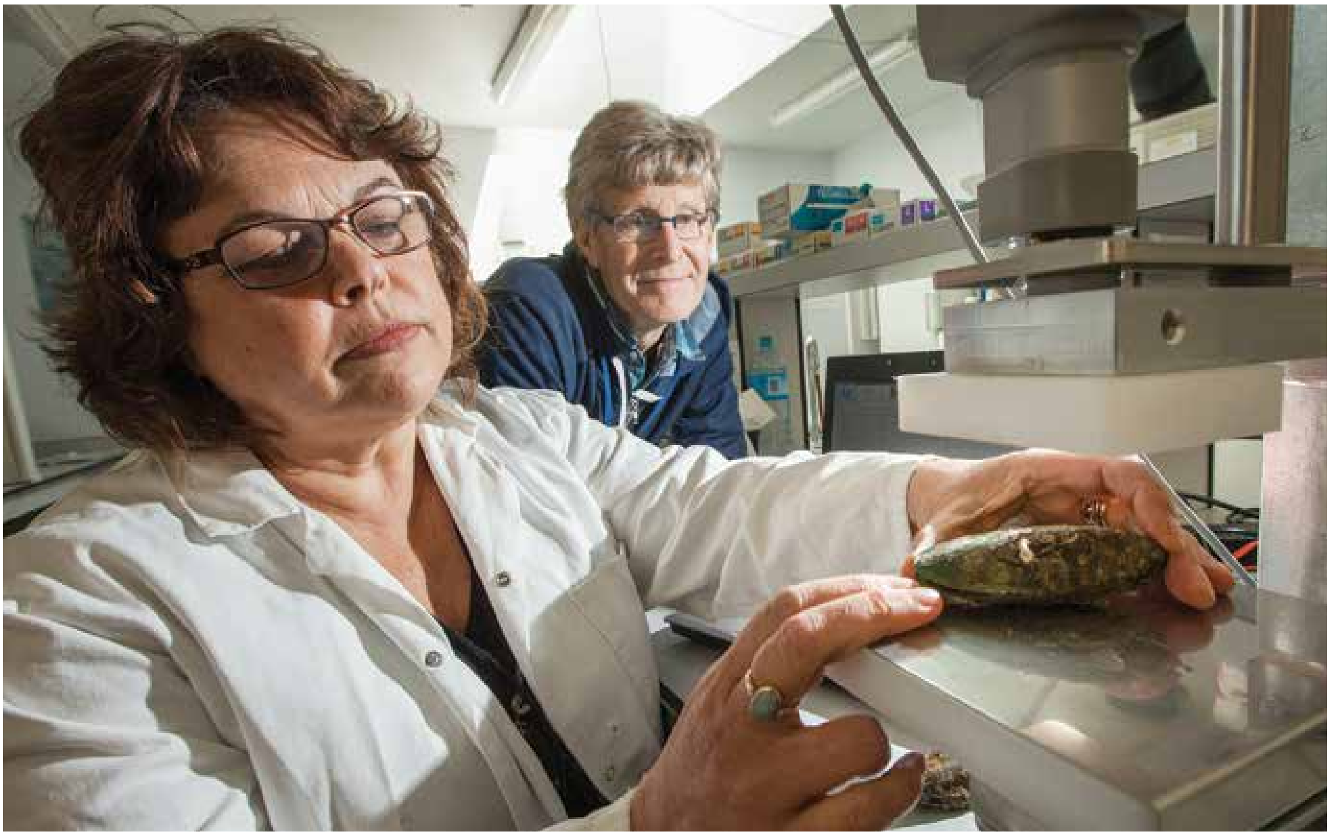
He remains grateful for the evidence provided by science that has helped grow the industry, but cautions that the business is "notoriously difficult".

"Weather mechanisms are critical, any research that can look into that is very valuable. So would be knowing the complete hydrology of Golden Bay and its relationship to the biology – I'd love to see that full scientific picture and it would help immensely with management of the farms."

NIWA is spearheading several research projects that are beginning to unlock some of the triggers that drive mussel production – from the reliability of spat (settled larvae) production to whether the strength of the shells influences the quality of the flesh.

One of those projects is a combination of NIWA's climate and marine ecological science capabilities.

Mussel power



NIWA's Jeanie Stenton-Dozey and John Zeldis measure shell strength in the 'Mussel Crusher'. Variations in fatty and amino acids, sex, shell dimensions, and body weight are also recorded at NIWA's site in Christchurch. (*Joseph Johnson*)

Each month NIWA releases its Seasonal Climate Outlook, which forecasts weather probabilities around New Zealand for the next three months. The rural sector uses these outlooks to help them prepare – especially this year with El Niño threatening to ramp up its intensity.

Now, NIWA Principal Scientist Marine Ecology, Dr John Zeldis, is developing something similar specifically for the mussel industry in the Marlborough Sounds, based on his collaborative research with the industry. Farmers could use such forecasts to more accurately determine the best time to harvest, or whether to harvest at all, or seed new lines, as well as gain a far better understanding of how climate affects their business.

One of the key elements that has enabled Zeldis to develop this capability has been a detailed set of data on mussel meat yield in Pelorus Sound collected by seafood company Sealord between 1997 and 2005.

"Every time a line was harvested, they took 20 mussels off and weighed their meat." There were 13,000 individual records in this data set, giving a detailed picture of variation in meat yield per mussel.

Two years into this data collection, mussel meat yield began to drop, until it was 20 per cent below normal. The industry was worried that they had over-stocked the Sounds with mussels. The slump in production lasted for three years before the crops recovered in 2002.

Fortuitously during this period another data set, this time documenting water quality, was also being collected in a collaboration between an industry consortium (Marlborough Shellfish Quality Programme) and NIWA. These data included information on the amount of phytoplankton and seston available. Seston is suspended organic matter (including phytoplankton) that floats in the water, which constitutes mussel food.

Zeldis discovered that by relating mussel meat yield fluctuations to a number of climatic factors, he could see a useful relationship between climate and the supply of food for mussels. Furthermore, the meat yield fluctuations observed between 1997 and 2005 occurred independently of farm stocking rates. In other words, mussel yield is driven by the climate and not related to farm stocking rates.

"Changes in production aren't caused by the intensity of farming; they are caused by climate."

What also became clear to Zeldis was just how crucial the occurrence of upwelling in Cook Strait was to the mussels. This upwelling, strongest in El Niño summers, supplies nitrogen-rich water from the Strait into Pelorus Sound, enabling the seston to proliferate.

"Upwelling is related to winds and is often detected as cool sea temperatures. Westerly winds drive the upwelling, and that's when we see cold water in western Cook Strait and near the entrance of Pelorus Sound. In terms of bringing nutrients toward the surface, upwelling is most effective between October and March and almost completely disappears over winter."

In winter, however, the mussels' food supply is influenced by winter rain and increased flow rates of the Pelorus River feeding into the Sound.

What Zeldis wanted to know was whether it was possible to use that information to forecast seasonal production.

"It looks very encouraging – our studies show it may be possible to predict mussel production in Pelorus Sound for time periods of three to six months into the future."

The process is complex – wind and river flows are not forecastable and had to be substituted with equivalent variables to make the forecast model work. But testing using historic yield and climate data has produced some outstanding results. "The predictions were just as good, if not better, and we are pretty confident we have the variables that are forecastable to predict mussel yield."

There is still some work to be done on some "fuzzy" areas in the model. But Zeldis says they should know by early next year what level of confidence can be ascribed to the forecasting.

It will then be up to the industry to decide how to use it – but the benefits seem obvious: the ability to forecast growing conditions for the next six months, information about the longevity of good or bad conditions and, ultimately, improvements to the bottom line.

While Zeldis is focused on climate parameters, colleague Dr Jeanie Stenton-Dozey is taking a close look at the mussels themselves.

The marine ecologist knows that one good season of fat, juicy mussels isn't always followed by another, and she is applying her science to find out why.

The catalyst for her research was the harvest in the Firth of Thames in 2011, 2012 and 2014 – yield declined, the mussels themselves were skinny and the flesh wasn't in good enough condition for the food market.

Debate in some parts of the industry centred on whether to leave the mussels on the lines to fatten up or harvest them and look for other markets.

Fortunately, if a mussel can't meet the standards for the export food market, it can be processed for the nutraceutical market – provided the omega and fatty acid contents are retained.

Greenshell™ mussels are purported to have anti-inflammatory properties that are easily absorbed by humans as omega-3 fatty acids, amino acids, minerals and carbohydrates. Freeze-dried mussel powder, taken as an oral dietary supplement, has found a steady market, particularly in Germany and the US. In the year to April, $9.2 million of powder was exported along with $23 million of mussel oil.

Stenton-Dozey wanted to know if she could identify trends in the condition of mussels that would enable farmers to pinpoint the best time to harvest and maximise the value.

Marlborough Sounds mussel farm. (*AquacultureNZ*)

Ellie Kerrisk from SPATnz examines a flask of microalgae grown as mussel food in the hatchery. (*Tim Cuff, SPATnz*)

This year she began a new three-year monitoring project – every two months mussels arrive at her Christchurch base from the Firth of Thames, Marlborough Sounds and Stewart Island for analysis. Body dimensions are measured, along with flesh weight, gonad weight and reproductive conditions. The fatty and omega acid profiles are measured, seasonal variation is assessed, and from that a library of mussel data is beginning to grow.

"At the same time we are collecting information on the environmental parameters such as water temperature, turbidity, nutrient levels and chlorophyll-a levels, to get a better handle on the relationship between the mussels and their growing conditions."

It is early days, but Stenton-Dozey believes a food supply issue is most likely to be the key factor in poor mussel production.

"It's not the stock. But it could be combinations of low food supply, long sustained high temperatures which affect metabolic rates, and long periods of stratified water preventing nutrients reaching the light-filled surface waters where plankton need to grow."

However, there is no mussel industry without spat, and that too is something of an enigma. There are three sources of spat in New Zealand. Currently, most of the spat is harvested from the wild, with up to 90% harvested from Ninety Mile Beach in Northland, where small pieces of algae, sponges, and other marine debris on which mussel spat have settled (referred to as Kaitaia spat) wash up onto the beach in particular weather. The spat, along with all the seaweed and debris they are attached to, are collected and transported to mussel farms around the country. Exactly where the Northland adult mussel beds are is a mystery. The spatfalls happen in late spring and through the summer, although NIWA marine scientist Dr Ken Grange says over the past couple of years, spat hasn't come ashore as often or in as much volume as previously.

Wild spat is also harvested from the mussel culture regions of Marlborough Sounds and Tasman/Golden Bays where farmers hang out hairy 'Christmas tree' ropes that mimic the settlement surfaces preferred by the larvae. The most recent development is a state-of-the-art hatchery, SPATnz, which opened in Nelson this year aiming to supply 30% of the industry's spat needs by 2020.

Having several sources of spat is a smart strategy for ensuring sustainable production, but not all the spat survive the journey to the grow-out areas and Ken Grange is keen to build on previous NIWA research to find out why. Would mussels ultimately fare better if they were transported under different conditions? Are they getting enough oxygen as they are trucked south? Should the spat be stripped off the seaweed before farmers get it?

"There is not a lot of research into issues such as oxygen depletion at the moment. We want to take some of the spat to our Northland Marine Research Centre at Bream Bay (near Whangarei) where we can keep it for a couple of weeks and fatten it up. Or maybe we will try to encourage it to leave the seaweed so we can get it to farmers in better condition with no debris, which would mean farmers getting more spat for their money."

Dr Grange intends to compare the success of spat handled in these novel ways with spat handled as it is now, with the aim of improving the existing guidelines on spat handling that would cover temperature, oxygen rates, humidity and optimum harvest times. This research will take another season to complete.

Life for the spat once they have been seeded onto the culture ropes in the mussel farms continues to be challenging because there they have to compete for food with other marine creatures, including each other, are preyed on by fish that take advantage of the delicious smorgasbord prepared for them by hard-working mussel farmers, and have to deal with the changing environment that Mother Nature serves up.

It is these processes that are the focus of Dr Barb Hayden, NIWA's Chief Scientist, Coasts and Oceans, who knows from many years working with the industry that improving the 'retention' of spat on the mussel ropes will make a significant difference to farm productivity.

This research is helping to build a more robust industry that is increasingly important to New Zealand's brand and to the diets of New Zealanders. If there's any evidence needed of that fact, it can be found at this year's South Island Farmer of the Year competition – won for the first time by a member of the aquaculture industry – John Young, Managing Director and part owner of Clearwater Mussels and a New Zealand aquaculture pioneer.

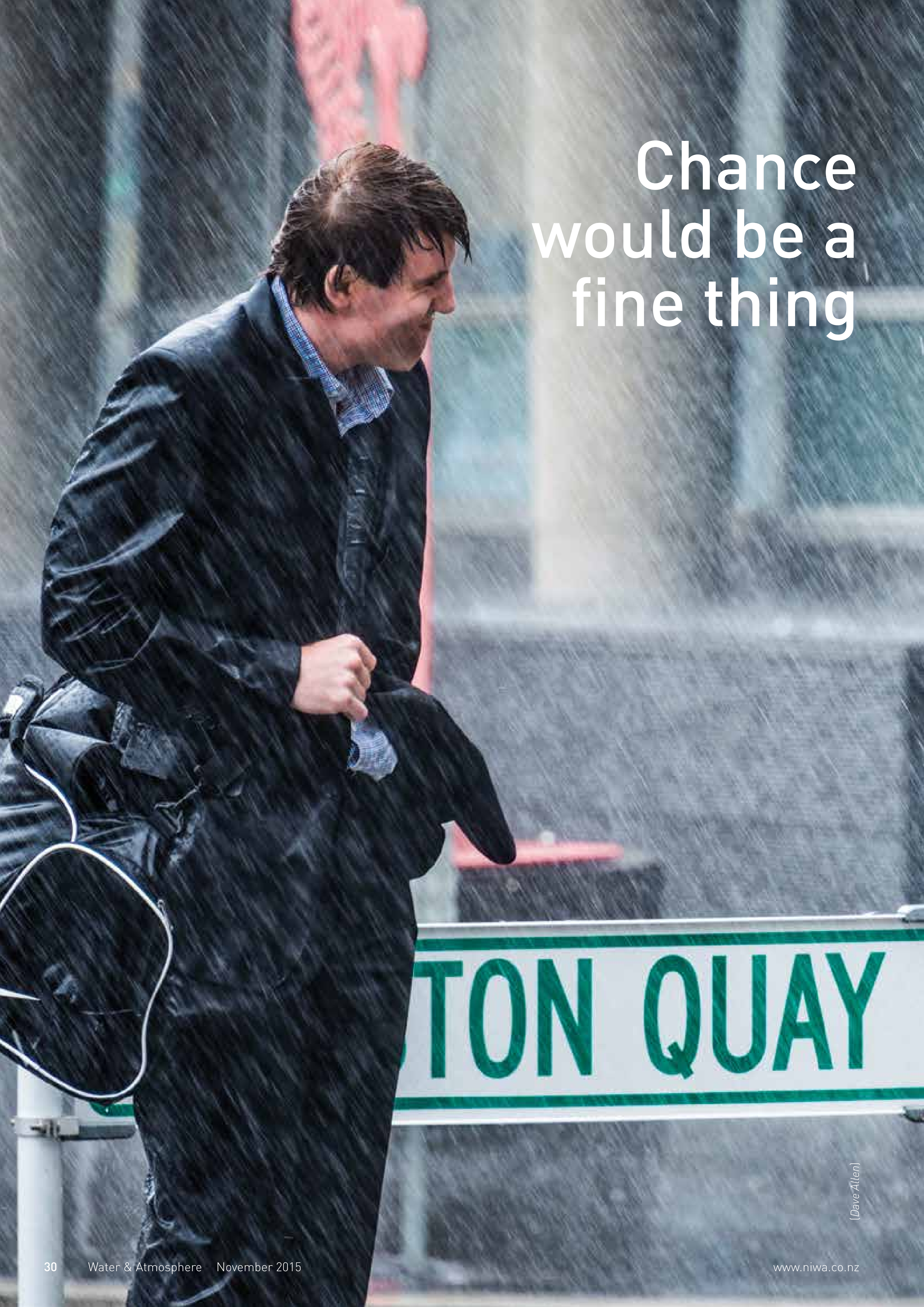
Need more evidence? Take a look at the industry's sustainable growth story:

http://aquaculture.org.nz/wp-content/uploads/2012/12/A-sustaianble-growth-story1.pdf

And next time you're at the supermarket, take a look at the seafood display – it's changed.

(Dave Allen)

Chance would be a fine thing



[Dave Allen]

NIWA's climate gurus are using statistical tools to improve seasonal climate forecasts.

Do meteorologists forecast rain so they get the golf course to themselves? This observation on Larry David's *Curb Your Enthusiasm* was backed up by US analysis, which showed that when a 100 per cent chance of rain was forecast in Kansas, it did not rain at all one-third of the time.

Despite glitches, short-term weather forecasts, up to 10 days ahead, are one of the great success stories of science and statistics. The average accuracy is about 70 per cent in temperature forecasts and 60 per cent in rainfall forecasts.

Forecasts are based on models of the weather. Data on what is currently happening are fed into a number of models. The forecasts are built from an assessment of what those models say is likely to happen.

A big part of the improvement is due to statistical modelling. Climatologists compare what they forecast with what weather actually does. Consistent inaccuracies can be corrected. This 'validation' helps them refine weather models, and helps people interpret them better.

The US National Weather Service found that human interpretation and consensus based on validation analyses of when models were right and wrong improve the accuracy of rain forecasts by about 25 per cent over the computer models. Human judgement improves temperature forecasts by about 10 per cent.

While short-term weather forecasts now have a high degree of reliability, climate forecasts – long-range estimates of what will happen in future seasons – are far less reliable. They are currently accurate only about 33 per cent of the time. Climatologists are turning their statistical tools to the task of improving this form of forecasting.

Dr Nico Fauchereau, who runs NIWA's Seasonal Forecasting Project, providing forecasts of approaching seasons, says the challenge of long-range forecasting is the randomness inherent in the climate.

"The climate itself hasn't yet settled on what it will do next season – so we can't forecast it with the certainty we have for tomorrow's weather. You can't predict something where outcomes are influenced by a massive degree of randomness."

The scale of chaos in weather is breathtaking. The number of molecules interacting in the Earth's atmosphere has been estimated at 100 tredecillion – that's a 1 followed by 44 zeros. Perfect weather predictions would have to account for all those molecules and solve equations for their interactions all at once. A change in even one of the interactions could change exponentially the interactions of millions of others.

If you could imagine correctly predicting the outcome of every person on Earth tossing a coin 1000 times, you'd still be nowhere near the degree of complexity required to forecast seasons.

Fauchereau says that the chaos is seen as noise in weather data. "For long-range outlooks we're looking for clear signals of a dominant trend influencing the weather. If there's no clear signal, noise dominates the data.

"In a strong El Niño – such as the one that is currently affecting the Pacific – the accuracy of forecasts is generally better.

"When there is no clear, large-scale signal, things can be more muddy; the climate is not 'steered' in any particular direction, and our confidence in forecasts is generally lower."

Another factor that makes seasonal forecasting challenging is New Zealand's geography.

'In a strong El Niño the accuracy of forecasts is generally better' – Nico Fauchereau. (*Dave Allen*)

Chance would be a fine thing

New Zealand lies between the sub-tropics and the mid-latitudes, and the potential for predictability decreases significantly between the tropics and New Zealand's latitude.

"We could improve our seasonal forecasts if we could move New Zealand a few tens of degrees northwards," says Fauchereau.

He says New Zealand's geography makes forecasting, especially long range, even tougher.

"For a small land mass like New Zealand, the distribution of sea surface temperature plays the biggest role in our weather.

"That means our seasons are influenced by a wide range of regional weather signals. Outside the El Niño and La Niña effects, it's hard to estimate which signal will be most influential on future weather."

Dr Brett Mullan, NIWA's Principal Scientist, Climate Variability, says that even with this uncertainty long-range forecasts are valued by many sectors, such as farmers, emergency services, regional planners and policymakers.

"They need to know what to expect so they can manage their resources. The type of detail demanded is less than for weather forecasts – customers need to know whether it will be hotter and drier than normal, not the exact temperatures. But accuracy matters even at this level of generalisation."

The need for accuracy and the implications of errors were amply demonstrated in 2009, when the UK Met Office forecast a 'barbecue summer'. Unfortunately, the season turned into one of the wettest summers on record, and led to the organisation ending its long-term outlooks.

Mullan says that while NIWA looks at climate on a monthly basis, it issues three-monthly forecasts and believes they are useful as an indication of the expected climate.

"We need an average period of at least three months to predict climate signals with some reliability. The three-month period is a compromise between averaging out the randomness and retaining the maximum amount of skill in the forecasts.

"Our forecast breaks New Zealand into six regions, which is not a fine resolution but is a level at which we're comfortable forecasting. There are three categories for forecasting temperature and precipitation: below normal, normal, and above normal. Each possibility is given a percentage chance of its occurring."

For example, at the start of October 2015 NIWA's climate outlook was that for the next three months there was a 40 per cent chance that temperatures would be near average and a 40–45 per cent chance that they would be below average for all of New Zealand.

There was also a 40 per cent chance that rainfall would be near the seasonal normal and a 40–45 per cent chance of it being below normal in the north and east of the North Island.

"Farmers, emergency services, regional planners and policymakers need to know what to expect, so they can manage their resources" – Brett Mullan. (*Dave Allen*)

The north of the South Island had a 35 per cent chance of being near normal and a 40 per cent chance of below normal.

When NIWA's climate team meets each month to assess the coming season from dynamical model forecasts and statistical models, it looks at validation data for the previous forecasts.

"Consensus generally does better than most individual models, and no model does best all the time."

Mullan explains that forecasts are based on both local (NIWA) models and international models. Some of the models are 'deterministic' and assume no randomness is involved, but more and more models these days take account of randomness by running 'ensembles' of forecasts – multiple forecasts starting with slightly different initial weather patterns.

"We compare the actual climate – the patterns, and precipitation and temperature – with the forecasts of models.

"We keep track of the weighting and human reasoning that go into each seasonal forecast."

A record is kept that reveals the extent to which nine different models have correctly estimated previous seasonal and monthly forecasts.

NIWA's Dr Trevor Carey-Smith heads the Automated Validation System project, an attempt to use these data to weight the results of each model according to its performance in the real world. The system will automatically generate forecasts from each model, modified to account for their accuracy in certain conditions.

"We're building algorithms that will weigh the influence of the individual models when they are merged to produce a single forecast.

"Not only is validation influencing the accuracy of the individual models, it is ensuring that the most accurate models have a greater influence on the final forecast.

"Validation ensures that the most accurate climate models have greater influence over the final forecast" – Trevor Carey-Smith. (*Dave Allen*)

"Automated statistical modelling can look at the conditions and predict from past performance which of the models will be more accurate."

Carey-Smith's project will take the statistical forecasts one step further, analysing the success of models on a location basis.

"We provide a regional seasonal forecast, but variability within regions means users apply their own experiences to their locations. If we're predicting a 75 per cent chance that it will be drier than normal for a region, and their locations are always drier than the region as a whole, their experiences will differ.

"In the future we'd like to use the automated validation to produce forecasts of local variations from the regional forecast."

Brett Mullan warns of the difficulty of the challenge that the climate team has set itself, and reasserts the value of human intervention.

"The task is made much harder by the fact that the core models themselves are always being changed to improve their accuracy. That means that statistics looking at the past performance may no longer be relevant.

"Statistical models and automated validation are going to improve the accuracy of seasonal forecasts in normal conditions and with strong climate signals like El Niños. But at the moment it's humans who are best at recognising and responding to the weird and unusual patterns. We still do random best."

Mullan says the introduction of validation and probabilities to the forecast has been a major step for consumers of weather information.

"The probability of the outcomes reflects the inherently uncertain state of the long-term climate. Yet there is enough information in the forecast odds to add value to regular economic decisions.

"When certainty is high the signal is strong – and people ought to pay attention to the possibility of droughts or high rainfall. Over the course of several seasons, this knowledge and use of climatic odds translate into dollars saved.

"Three-month outlooks are designed to help people understand developing situations against the normal seasonal outcomes – while being wary of unexpected outcomes," he says.

'FitzRoy' named after first 'weatherman'

The NIWA supercomputer that crunches seasonal data is named after Robert FitzRoy, a Governor of New Zealand and captain of the *Beagle* on Charles Darwin's voyage that led to his theory of natural selection.

On returning to Britain, FitzRoy's fascination with the weather on sailing voyages led to a late career change, at 54 years old, to 'Meteorological Statist to the Board of Trade'. His new department was intended to design wind charts for navigation.

FitzRoy was inspired to develop charts for what he called "forecasting the weather" by the sinking of the boat *Royal Charter* in a terrible storm in 1859. Land stations were established to use the new telegraph to transmit to him daily reports of weather at set times. FitzRoy assessed the reports to judge whether to issue storm warnings for ports. When he realised that the sorts of data he was collecting had wider usage, he started turning them into the first-ever daily weather forecasts, published in *The Times* in 1861.

While the forecasts quickly became massively popular, they were also lampooned for their regular inaccuracy. In May 1862 The Age wrote ahead of the famous Derby horse race that, as Admiral FitzRoy had forecast moderate to fresh winds with some showers, it would be "a remarkably fine day, and … the umbrellas might be left behind".

There were more serious challenges to FitzRoy's forecasts. Some politicians complained about the cost of the telegraphs. The scientific community was sceptical of his methods, claiming they lacked a coherent theory. The maritime sector was supportive, but others begrudged workdays lost to mistaken storm forecasts.

In battle with critics, FitzRoy worked hard to decode the British weather. He published a book and gave lectures, but in 1865 he retired, exhausted and beset by depression. He took his own life that year.

NIWA Photography Award entries

Spawning sea urchins. This urchin *Sterechinus neumayeri* is a broadcast spawner, liberating its seed into the water column. (*Peter Marriott*)

Ice shake. A scientist empties icy drill chips during the drilling of an ice core. Taylor Glacier, Antarctica. (*Hinrich Schaefer*)

Winner – Public Choice

A tui on Tiritiri Matangi Island, Hauraki Gulf. (*Alvin Setiawan*)

NIWA Photography Award entries

View of the crater lake atop New Zealand's largest active volcano, Mt Ruapehu. If you look closely, steam can be seen above the warm crater lake surface. (*Nava Fadaeff*)

Returning some common smelt to Te Waihora (Lake Ellesmere). (*Shannon Crow*)

Gannet on the wing at Farewell Spit – changing direction before to diving for fish. (*Ron Murdoch*)

NIWA Photography Awards entries

Winner – Our Places

Three penguins run beside a track of broken ice created by the US icebreaker *Nathaniel Palmer* into McMurdo Sound. (*Rob Murdoch*)

Winner – Our People

Scientific diver Crispin Middleton is surrounded by panicked Starry Toado Pufferfish at the Poor Knights Islands Marine Reserve. (*Crispin Middleton*)

Two scientists on reconnaissance for a potential ice core sampling site. Although there is debris at the foot of the ice cliff, ice fall is very rare at the cold-based glaciers of the McMurdo Dry Valleys, especially in the early morning, when temperatures are low and even from the cold of the night. (*Hinrich Schaefer*)

Profile

The sky's no limit

Fascinated by what was above him as a young boy, peering skyward at stars at night and clouds by day, it was a natural progression for Sam Dean to forge a career in atmospheric and climate research.

Born in Kilmarnock, Scotland, Dean came to New Zealand with his father and Kiwi mother in 1976.

"We came on a rusty Russian ship," says the recently appointed Chief Scientist at NIWA's Climate and Atmosphere Centre.

"It took six weeks and the people in the cabin next door didn't even know I was on the boat. It must have left a lasting impression because nowadays you won't see me on NIWA's deepwater research vessel *Tangaroa* – I've been to Antarctica, but I flew."

But an affinity with the space above him has remained strong.

Growing up in Devonport and then in Nelson, Dean decided to turn his passion into a career and went to the University of Canterbury.

"I went there because I knew I wanted to do physics but I was also really interested in astronomy and astrophysics.

"The change for me was around my third year. There was a professor named Bryan Lawrence who taught a course on geophysical fluid dynamics. This described how air moves in the atmosphere, how energy is exchanged and when water changes state – creating equations to pull out an understanding of weather systems and how the air around us will move in response to everything else around it.

"It was a beautiful insight for me, that you could take maths and do something that not only describes the world around us now, but also allows you to predict the future."

Having gained his PhD in clouds and climate modelling, Dean headed to the United Kingdom – by air, of course – to undertake a postdoctorate research role at the University of Oxford, measuring clouds from space using satellites. In 2006 he returned home to New Zealand to join NIWA.

It was then that he took a keen interest in the influence of human beings on climate systems.

Climate change, Dean says, is here and already having an impact on New Zealand.

"Extreme rainfall – that's one of the ways New Zealand will most significantly feel the effects of climate change. Extreme rainfall is already likely to be more intense, and we've worked to use climate models and observations to understand how much climate change is already influencing New Zealand.

"I'm driven by understanding the world around us. I don't believe in using fear to motivate people. I want them to be informed to make decisions based on good science.

"I do think it's important that we try to understand how much climate change is likely to affect New Zealand in the years ahead. I've spent a lot of time researching this question myself.

"Then, once you understand that significant change is coming and some of it is now inevitable, planning how we will adapt and thrive in a changing climate becomes a priority.

"One example of this is the need for timely and accurate forecasts for ever-more-severe weather events. With the increasing exposure of our infrastructure to hazards such as flooding from rainfall and storm surge, our ability to provide advance warning of events will be critical to ensuring we are resilient in the future. That's why forecasting the impacts of severe weather events has become another focus for me."

All of this brings us back to Dean's new role. After nearly 10 years at NIWA Dean recently stepped into the challenging role of Chief Scientist.

"What I bring to the role is a very wide personal background in climate, atmosphere and hazards science. I want to use that knowledge as best I can to help keep NIWA at the forefront of a national and international science environment that is rapidly evolving.

"On top of that, the aspect that I'm most looking forward to is working to support our fantastic scientists, to promote the great things we are doing in this area and to grow our capabilities.

"It's a great strength of NIWA that we work to maintain a strong backbone of fundamental research, but also look to apply that knowledge in developing top-quality science applications and decision-support tools.

"For me it is the approach that all science must take in the future and lies at the heart of solving the climate change problem."

Given that the problem has, in part, been created by science and technology, it seems sensible that science and technology can be employed to help solve it.

"There's a certain investment, political will and common sense of purpose that's required, but it's doable," Dean says.

NIWA's Chief Scientist for Climate and Atmosphere and Hazards, Sam Dean. (*Dave Allen*)

"I'm a great believer in the power of humankind and our ability to innovate and do good science to work our way through issues."

Dean doesn't just talk the talk – he walks, rather rides, it as well. When the Wellington weather's conducive he travels to work on his electric-assisted mountain bike. The bike is a small example of the way science, technology and innovation can change our lives for the better, Dean says.

Here and now though, Dean's finding that the cloud of climate change has a silver lining.

"I certainly enjoy extreme weather events – you kind of have to, living in Wellington. We live on top of a hill in Brooklyn with a magnificent view of the mountains. We get southerlies, northerlies, rain … I love that.

"I certainly appreciate New Zealand for its dynamic weather and the beautiful days have to be celebrated.

Solutions

Fish software now standard

A NIWA-developed advanced software package is becoming the international standard in the assessment and management of fish stocks, including some of the world's most prized species.

CASAL (C++ Algorithmic Stock Assessment Laboratory) is an advanced software package developed by NIWA to provide quantitative assessments of the status of most of New Zealand's fish stocks and shellfish fisheries for the Ministry for Primary Industries (MPI).

CASAL is also proving a major catch internationally, with overseas agencies adopting the package to assess Patagonian and Antarctic toothfish and broadbill swordfish fisheries.

NIWA Principal Scientist and CASAL Development Team leader Dr Alistair Dunn says CASAL is being used by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), an agency established in 1982 with the objective of conserving Antarctic marine life.

CCAMLR uses CASAL to assess stocks of Antarctic (*Dissostichus mawsoni*) and Patagonian (*Dissostichus eleginoides*) toothfish, with Japan, Australia, the United Kingdom and France also adopting the package to monitor numbers and the management of the valuable fishery.

"We developed the methodology using the types of data for CCAMLR, and everyone else adopted it because it was a really easy way for them to get up to the same space in an integrated way and to report the results using our package," says Dunn.

"The inputs and the outputs are all standard, so we can all read them. There are lots of language barriers in international communities, so this gives us a standard language to use on the topic."

The CASAL software implements a generalised age- or length-structured fish stock assessment model that allows a great deal of choice in specifying population dynamics, parameter estimation and model outputs.

Designed for flexibility, CASAL also optionally structures population by sex, maturity and/or growth path. It can be used for a single stock for a single fishery or for multiple stocks, areas and/or fishing methods.

The data used can be from many sources; for example, catch-at-age and catch-at-size data from commercial fishing, survey and other biomass indices, survey catch-at-age and catch-at-size data, and tag-release and tag-recapture data.

(Peter Marriott)

"It allows us to undertake assessments of marine species such as fish using best-practice methods in a relatively straightforward and standard way," says Dunn.

"It's a generalised piece of software that allows us to try out different approaches and assumptions quickly and easily and assess which assumptions are likely to be true and which aren't."

CASAL was developed as a direct response to other, more limited, assessment tools.

"Until now, people writing assessment packages have solved the specific problems in front of them, and they've written specific pieces of code for those problems.

"What we set out to do with CASAL was to write something that applied to any type of problem, using switches or commands to replicate any structure that might be chosen, be it species, age structure or length-base models – we can include a wide variety of life history characteristics across different time periods using different observations.

"CASAL means any structure can be replicated and modelled."

Sustainable management

Ultimately, CASAL is helping more efficient and sustainable management of fisheries, says Dunn.

In New Zealand, fisheries often safely operate in a target biomass (a total mass of breeding fish compared with the population estimate before fishing began) range of about 40 per cent, depending on species and stock. A biomass level of about 20 per cent represents an overfished stock and one below 10 per cent represents a stock that has collapsed and is at risk of not recovering.

"CASAL can constantly readjust and manage inputs around a target quickly, so we can see how to maximise a catch without damaging the stock population.

"For example, in the past 10 years we've moved from a situation with our middle-depth (hoki) and deepwater (orange roughy) stocks where there was some pressure coming on and stocks were starting to decline. CASAL can model outcomes for a wide range of stocks. It has been able to help fisheries' managers make changes in total allowable catch, so some stocks are now looking quite healthy."

While CASAL has been a huge success it has become apparent that, despite occasional bug fixes and updates, it is getting a little long in the tooth. To bring it up to speed, Dunn and his team – in conjunction with MPI – have been working on CASAL II.

"We're planning to go live with CASAL II in about six months," Dunn says. "CASAL was a great piece of code for its time, but we've gone back to the drawing board and taken all the learnings to build a unique, open-source product."

CASAL II will comprise a modular approach, with standard interfaces that can be clipped together like Lego blocks to "do all the things CASAL can do now and things we haven't even thought of yet".

It is a tool that co-funder MPI is looking forward to using.

"The original CASAL was state of the art. It was up there with the best in the world," says MPI Chief Scientist Pamela Mace.

"But there are some things CASAL can't do, or can't do very easily, so we've asked for more flexibility and a more modular approach. We're looking forward to seeing CASAL II, and progress reports to date sound very good."

NIWA
enhancing the value of New Zealand's natural resources

NIWA (the National Institute of Water & Atmospheric Research) was established as a Crown Research Institute in 1992. It operates as a stand-alone company with its own Board of Directors, and is wholly owned by the New Zealand Government.

NIWA's expertise is in:

- Aquaculture
- Atmosphere
- Biodiversity and biosecurity
- Climate
- Coasts
- Renewable energy
- Fisheries
- Freshwater and estuaries
- Māori development
- Natural hazards
- Environmental information
- Oceans
- Pacific rim

NIWA employs more than 600 scientists, technicians and support staff.

NIWA owns and operates nationally significant scientific infrastructure, including a fleet of research vessels, a high-performance computing facility and unique environmental monitoring networks, databases and collections.

Back cover:

A small group of Salvin's mollymawks chase a free meal behind a local fishing vessel as it makes its way across Cook Strait. (*Dave Allen*)

NIWA
Taihoro Nukurangi

enhancing the benefits of
New Zealand's natural resources