Earth Systems and Climate Change Hub

National Environmental Science Programme

Climate change in a land of extremes

Earth Systems and Climate Change Hub (2015–21)

Acknowledgement of Country

The NESP Earth Systems and Climate Change Hub acknowledges the Traditional Owners of the lands and seas that we live and work on across Australia, and pays respect to their Elders past, present and emerging. We honour and celebrate the spiritual, cultural and customary connections of Traditional Owners to Country, and its surrounding seas and oceans.

Table of contents

■ Above: Measuring greenhouse gas emissions at a mangrove forest. ISTOCK.COM/ TENEDOS
■ Cover image: Collecting data at Rockingham Lake. ISTOCK.COM/SOLSTOCK

Glossary

ACCESS	Australian Community Climate and Earth System Simulator
ACCESS-ESM1.5	ACCESS Earth Systems Model version 1.5
ACCESS-CM2	ACCESS Couple Model version 2.0
AFAC	Australasian Fire and Emergency Services Authorities Council
AM	Asymmetric Mode
AMOS	Australian Meteorological and Oceanographic Society
ARI	Average return interval
BoM	Bureau of Meteorology
CABLE	Community Atmosphere Biosphere Land Exchange
CCIA	Climate Change in Australia
CMIP5	Coupled Model Intercomparison Project 5
CMIP6	Coupled Model Intercomparison Project 6
CMSI	Climate Measurement Standards Initiative
CO_2	Carbon dioxide
COP25	United Nations Climate Change Conference of the Parties (2019)
CORDEX	Coordinated Regional Downscaling Experiment
COWCLIP	Coordinated Ocean Wave Climate Projections
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAWE	The Department of Agriculture, Water and the Environment
DCFP	Decadal Climate Forecasting Project
DPIR	Department of Primary Industry and Resources (NT)
EAC	East Australian Current
ECL	East coast low
EDDI	Evaporative Demand Drought Index
ENSO	El Niño–Southern Oscillation
ESI	Evaporative Stress Index
FFDI	Forest Fire Danger Index
GBR	Great Barrier Reef
$GtCO_2$	Gigatonnes carbon dioxide
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report (2013/14)
IPCC AR6	IPCC Sixth Assessment Report (due 2021/22)
IPO	Interdecadal Pacific Oscillation
MJO	Madden-Julian Oscillation
NCCARF	National Climate Change Adaptation Research Facility
NCCC	National Centre for Coasts and Climate
NESP	National Environmental Science Program
NFPGCC	National First Peoples Gathering on Climate Change (2021)
RCP	Representative concentration pathways
SAM	Southern Annular Mode
SBWHAC	Shark Bay World Heritage Advisory Committee
SROCCC	Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019)
Hub	NESP Earth Systems and Climate Change Hub
TSR Hub	NESP Threatened Species Recovery Hub
WHA	World Heritage Area

Foreword

Australia relies on world-leading climate change science to help manage the influence of a variable and changing climate on our environment, economy and communities. As a collaborative partnership under the Australian Government's National Environmental Science Program (NESP), the Earth Systems and Climate Change Hub (ESCC Hub) has been the cornerstone of this research.

The Hub was established in 2015 to ensure Australia's policy and management decisions were effectively informed by Earth systems and climate change science. Hub partners included the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology (BoM) and five universities: the Australian National University, University of Melbourne, Monash University, University of Tasmania and University of New South Wales. It quickly positioned itself as a trusted source of information, capable of delivering important benefits to government, the private sector and the wider Australian community. The Hub has worked collaboratively with five other NESP-funded research hubs, supporting decision-makers to better understand, manage and conserve Australia's environment.

Over the course of the Hub's history it has delivered critical knowledge in the field of climate change projections, improved understanding of coastal hazards and extreme events, and refined Australia's national climate modelling capability. Much of this science is responsible for the real on-ground outcomes delivered through the Hub, including establishing a new research facility for coastal protection and carbon sequestration, the National Centre for Coasts and Climate (NCCC), and translating climate change data and information into a framework for understanding risk and disclosure in the business and finance sector.

A key priority was to ensure that climate change information and advice met the needs of its end users and supported decision-making. The Hub covered significant ground in establishing respectful partnerships with First Nations peoples, and showed the value of co-designing climate change science research with a variety of environmental and industry managers.

The Hub's dedicated researchers have also demonstrated remarkable flexibility and resilience by providing critical input into the extreme events that unfolded over the past 18 months. This included delivering information relevant to policy development in the aftermath of Australia's Black Summer in 2019–20, and flagging an unprecedented opportunity during the COVID-19 pandemic to slow the upward trajectory of global carbon emissions. These achievements have longevity and impact well beyond the lifetime of the Hub.

I am confident that the Hub's work will play a critical role in the coming decades in ensuring climate change science is developed for the benefit of all Australians. I wish every success to the new Climate Systems Hub supported by the second phase of NESP, and would like to thank the Earth Systems and Climate Change Hub's partners, collaborators and stakeholders for the opportunity to advance understanding and management of Australia's changing and variable climate.

Professor David Karoly, Earth Systems and Climate Change Hub Leader

■ Clownfish, Great Barrier Reef. ISTOCK.COM/BRAD BOOTH

Executive summary

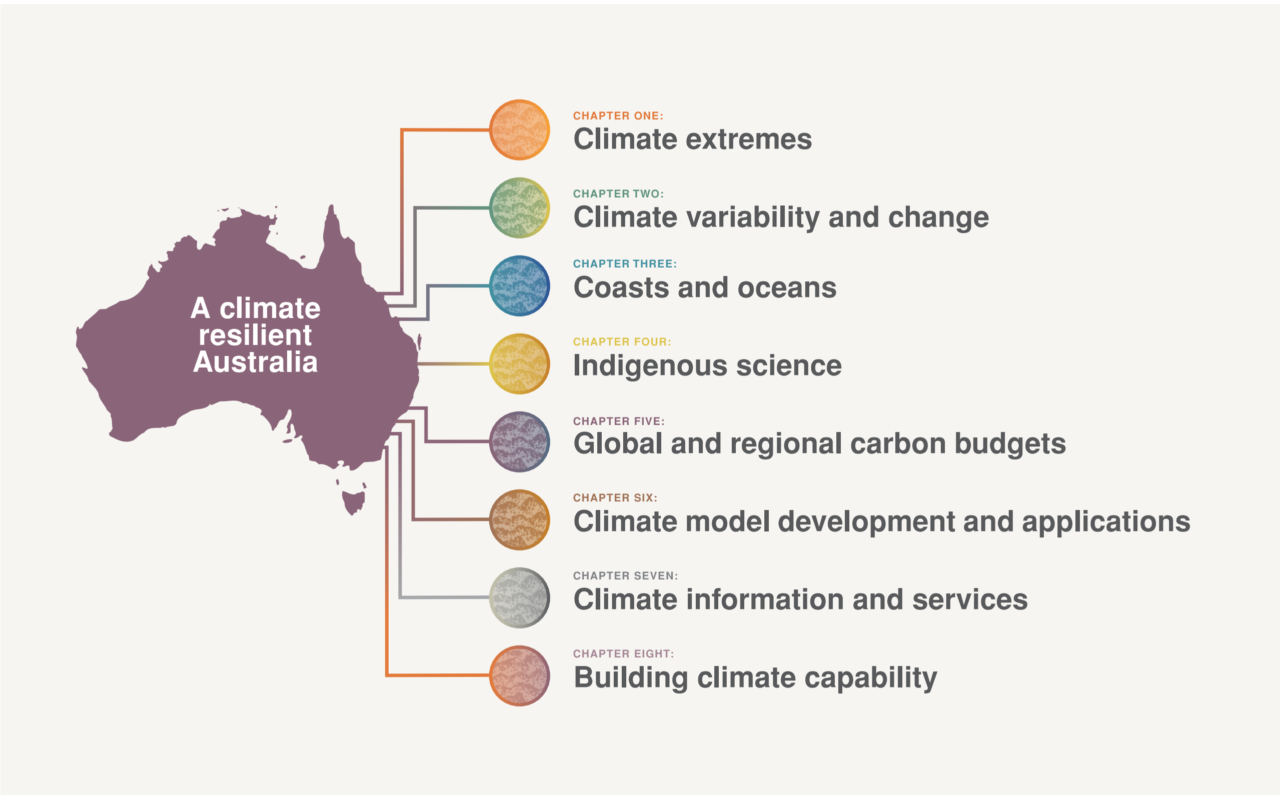
This report describes the Hub's achievements over its six-year existence. It is not intended to be a comprehensive report on all of the Hub's outputs but rather a summary that highlights how Hub research has contributed to a better understanding of Earth systems and climate change.

Efforts were focused around key areas of research and engagement to ensure a climate-resilient Australia.

The Hub's activities are represented in this report under eight interconnected key themes:

- Climate extremes
- Climate variability and change
- Coasts and oceans
- Indigenous science
- Global and regional carbon budgets
- Climate model development and applications
- Climate information and services
- Building climate capability.

Further information on the Hub's outputs, including a range of fact sheets and brochures, can be found at www.nespclimate.com.au.



■ The structure of this report reflects the Hub's activities, which were focussed around key areas of research and engagement to ensure a climate-resilient Australia.

Climate extremes

The cost of extreme climate events and associated disasters, such as bushfires, storm surges, drought and marine heatwaves, will increase as the global climate warms in response to ongoing greenhouse gas emissions. Understanding the underlying mechanisms of hazards and how they may change as the climate continues to warm is essential if we are to improve Australia's disaster preparedness.

The Hub has increased our understanding of extreme events, providing emergency services and disaster managers and a wider range of users with better quality, relevant and targeted information that will enhance our resilience to extreme weather and climate events.

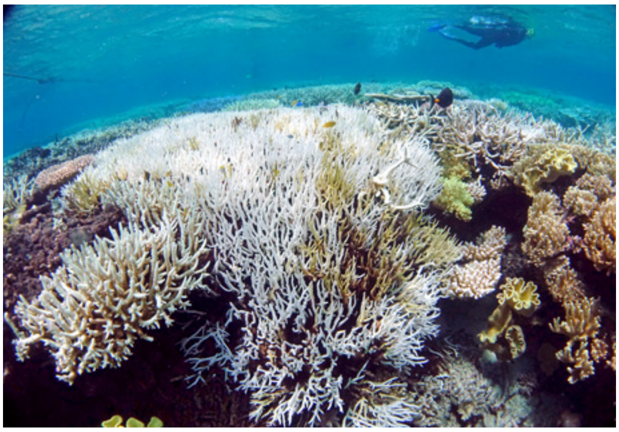
Understanding marine heatwaves, their predictability and impacts

Climate change has increased the intensity, duration and frequency of marine heatwaves (sustained periods of abnormally high temperatures in the ocean). This has a range of impacts on marine ecosystems and ocean-based industries, including seagrass and kelp forest dieback, coral bleaching and tropical disease incursions.

To adapt to and prepare for future marine heatwave events, marine and ocean managers need access to information on climate drivers and projections to improve planning and decision-making. Hub researchers delivered key information for Western Australia and Tasmania to support business planning and adaptation.

ISTOCK.COM/DAMOCEAN

■ Marine heatwaves have a range of impacts on marine ecosystems, including coral bleaching.



CHRIS JONES

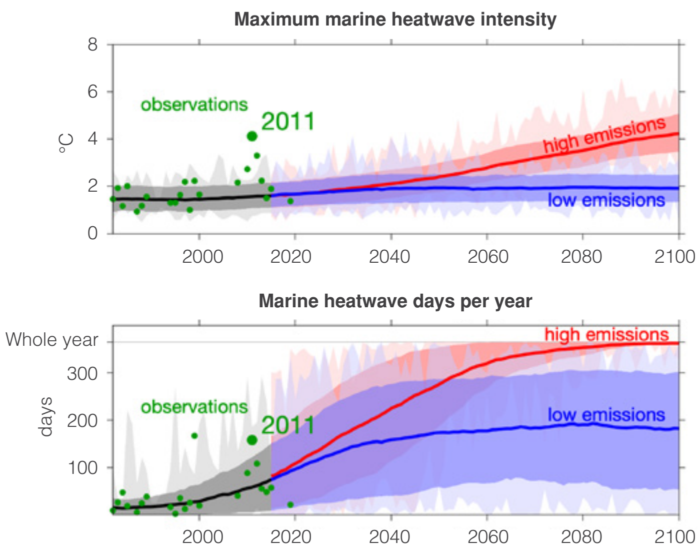
Western Australia

In 2011 Western Australia experienced its most devastating marine heatwave event in recent history, with temperatures 2.5° C above historical levels over a two-month period.

Occurring off the coast between Perth and Shark Bay, the impacts to the local environment, ecology, and ocean-dependent industries were extremely damaging and widespread. Several years after the heatwave only parts of the ecosystem have shown reasonable recovery, indicating its lasting effect on the region.

Hub researchers examined the likelihood of another extreme marine heatwave occurring in Western Australia under two possible future climate scenarios: a low-emissions scenario and a high-emissions scenario.

In today's climate, marine heatwaves similar in intensity and duration to the 2011 event occur approximately once every 80 years. Under a low-emissions scenario they are expected to occur once every 50 years by the end of the century, while under a high-emissions scenario they are projected to occur at least once every decade, and perhaps as often as every second year.



■ **Marine heatwave frequency and intensity is projected to increase more under a high emissions scenario compared to a low scenario.** Model projections from 17 CMIP5 models, under low (RCP2.6) and high (RCP8.5) emissions scenarios. Light shading denotes the full model ranges, darker shading the 66% likelihood range, and solid lines the model mean.

Tasmania

The Tasman Sea is a global hotspot for ocean warming, with sea temperatures rising at nearly four times the global average rate of ocean warming. In the summers of 2015–16 and 2017–18, two of the most intense marine heatwaves in the Tasman Sea in recent years occurred off the east coast of Tasmania. This was the result of a strengthening East Australian Current (EAC) (bringing warm tropical waters from the north) and a persistent atmospheric high-pressure system, which interacted with the background warming trend.

Marine heatwaves in the oceans around Tasmania pose risks to the region's aquaculture and fisher industries. The Hub used climate projections under two possible future scenarios (low emissions and high emissions) to find out how likely it would be for marine heatwaves of this magnitude to occur in the Tasman Sea again. Both scenarios pointed to increasing frequency with continued global warming.

A marine heatwave similar in intensity to those in 2015–16 and 2017–18 is currently expected to occur approximately once every 20 years. Under the low-emissions scenario, it is expected to occur once every 15 years by the end of the century, and under the high-emissions scenario, a marine heatwave is projected to occur almost every year.

Calculating the likely frequency of future marine heatwave events from modelled projections to help guide risk assessments and adaptation planning.

Tropical cyclones and the Great Barrier Reef

Tropical cyclones (intense low-pressure systems) are the most damaging weather events impacting northern Australia. An average of around 11 tropical cyclones form or move into the Australian region every year. Of these, around three pass within the Great Barrier Reef (GBR) Marine Park.

Developing and intensifying over warm tropical oceans such as the Coral Sea, tropical cyclones sustain very strong winds, extreme rainfall and destructive waves that can inflict catastrophic damage. Not surprisingly, the already-vulnerable coral and resident ecosystems of the GBR are exposed to extensive damage from powerful waves generated by cyclones.

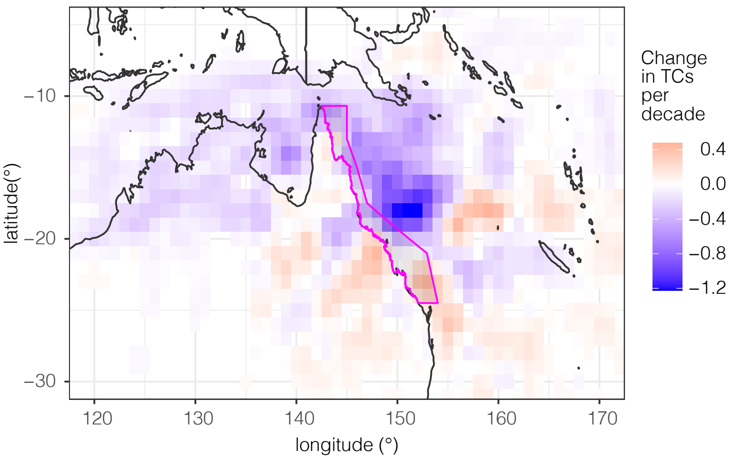
Hub researchers worked on ways to develop more detailed and regionally-specific tropical cyclone projections to help Reef managers plan for future cyclones.

This research indicated the likelihood of a greater proportion of intense tropical cyclones over the GBR in the future, as a result of the increasing energy in the climate system available to power tropical cyclones. While the overall number of annual projected cyclones across Australia is projected to decrease, rainfall associated with the more intense tropical cyclones is expected to increase, which has potential implications for changes in run-off from the land adjacent to the GBR. Increased sediment run-off into the GBR resulting from erosion has been linked to poor water quality and outbreaks of the crown-of-thorns starfish, adding to the stress caused by warming waters.

The Hub also found evidence to suggest that tropical cyclones around Australia may move slightly further poleward (south) under a warmer climate; a shift associated with warmer oceans and changing large-scale wind patterns. More research into this poleward shift is required before the data can be confidently used by decision-makers.

Further information on tropical cyclone projections in the Australian region is now available on the NESP Tropical Cyclone Projections Portal developed through the Hub. Features include observed modelled cyclone tracks, track density maps, coastal crossings, and seasonal cycle and annual frequency box plots.

Communicating potential changes in tropical cyclone frequency and location under future climates.



Tropical cyclone occurrence may increase slightly in the southern part of the Great Barrier Reef region and decrease in central and northern regions under a future warming climate. Projected changes in the average number of tropical cyclones (per decade in 1° × 1° box) that pass within 250 km of the Great Barrier Reef Marine Park (magenta boundary). This is shown for the change between two periods based on a selection of CMIP5 models: the historical climate (1970–2000) and the future climate (2070–2100) under a high emissions pathway, RCP8.5.

East coast lows and heavy rainfall

East coast lows (ECLs), low-pressure systems that form off the East Coast of Australia, can cause heavy rainfall, strong winds, large waves, widespread flooding and coastal erosion. They are capable of devastating impacts including injury, loss of life, infrastructure damage and large insurance losses. At the same time, they provide a major source of rainfall and storage replenishment. As the climate continues to warm, projections indicate that we can expect less frequent ECLs, but more intense rainfall being likely due to warmer air being able to contain more water in some cases. These future changes for ECLs are similar in some ways to what is projected for tropical cyclones, where fewer are projected to occur but with more intense rainfall.

Research from the Hub has significantly improved Australia's understanding of ECLs and how the intensity of extreme rainfall events may change in the future. This included a new understanding of the physical processes of ECLs (vertical structure and energy sources), and the implications for future changes in extreme rainfall, winds and coastal hazards along Australia's eastern seaboard.

Hub research has also improved our understanding of flood risk. In a warmer world where the atmosphere holds more moisture, we can expect very intense rainfall events (such as those associated with ECLs) to increase in intensity and volume. The increase in rainfall is particularly relevant for ECLs that occur closer to the coast, due to changes in ocean currents and large increases in sea surface temperatures. With 85% of Australia's population living near the coast, increasing rainfall intensity and volume has very real implications.

Based on a novel framework developed by the Hub for analysing compound events, extreme rainfall near eastern Australia was found to be most frequently caused by the simultaneous occurrence of an ECL, a thunderstorm and a front. Researchers also found that short duration (e.g., hourly) events produced by thunderstorms could potentially increase in intensity by about 15 per cent per degree of global warming.

Helping to ensure preparedness and resilience for Australians by understanding extreme weather hazards and how they may change in a warmer world.

Future extreme sea-level events

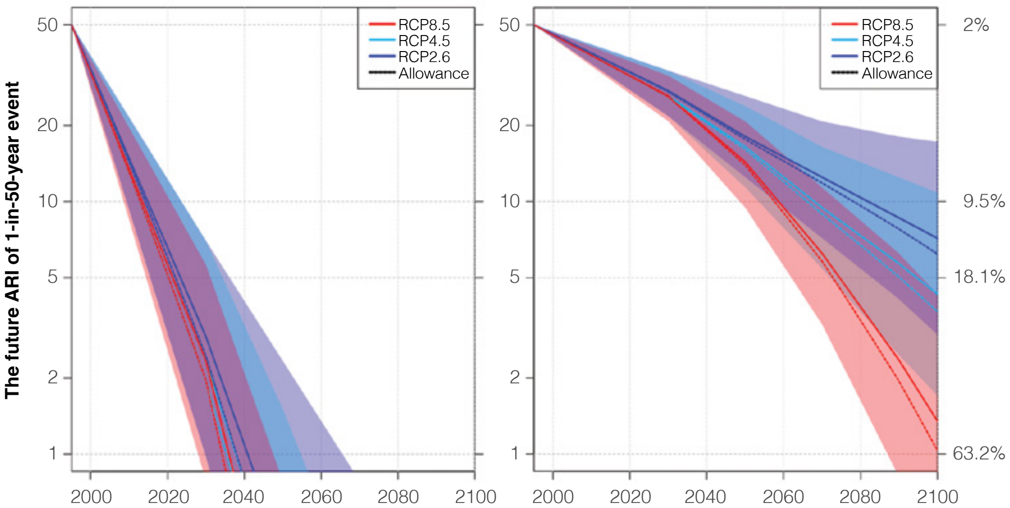
Currently, global sea-levels are rising at an average of 3.5 cm per decade, however, the rate of sea-level rise is not uniform around Australia. The associated impacts of sea-level rise also vary around our coastline, such as coastal inundation and erosion, which pose tangible risks to coastal communities, ecosystems and infrastructure.

To understand the risks of extreme sea-level events at different coastal locations around Australia, stakeholders such as coastal councils, authorities and practitioners need high-resolution information and data that includes comparisons of extreme sea-level rise impacts on protected harbours and inlets and neighbouring wave-exposed beaches.

Through analysis of a range of coastal and nearshore variables, including sea-level trends, extreme sea-levels and waves, researchers at the Hub set out to improve understanding of how marine and coastal extremes are changing under a warmer climate. This included an upgrade to the high-resolution sea-level rise calculator tool 'Canute', which features new sea-level rise projections as well as average return interval (ARI) plots.

Canute allows stakeholders to explore the impact of extreme sea-level events in protected harbours and open ocean beaches around the coastline of Australia. It's also responsive, allowing users to access information such as, 'If coastal inundation from a storm event in a given location was once considered a 1-in-100-year event, what would it be considered as in 20- or 30-years' time?'.

Plume plots of the change to a 1-in-50 year Average Recurrence Interval (ARI) event caused by sea-level rise for Sydney Harbor (left) and Narrabeen-Collaroy beach (right). Coloured regions indicate the Representative Concentration Pathway (RCP) projected 95% uncertainty ranges of the change in ARI due to sea-level rise (see colour key for RCPs). Right axis of each plots represents the Annual Exceedance Probability (AEP) as a percentage (%).



Changes in extreme sea-level rise in Sydney

Sea-level projections can be expressed via 'average return intervals' (ARI) which provides an estimated average time between events such as extreme sea-levels.

Using Canute, Hub researchers generated ARI plots for Sydney Harbour (a protected harbour) and Narrabeen–Collaroy beach (an open beach with an exposed coastline). The plots were generated under different representative concentration pathways (RCPs), a commonly used standard for climate projections, now available through the tool.

Open ocean beaches such as Narabeen–Collaroy are exposed to sea-level extremes, which are compounded by damaging surf conditions from sea waves (generated by local prevailing winds) and swell waves (regular, longer period waves generated by distant weather systems). This results in amplified extreme sea-levels through the process of wave set-up.

Canute demonstrates that higher extreme sea-levels projected to occur at Narrabeen–Collaroy would be larger than within Sydney Harbour, but an increase in the occurrence of extreme sea-levels under future sea-level rise is projected to have a greater impact on protected harbours than on wave-exposed beaches.

Keeping coastal managers informed of projections and risks associated with extreme sea-level events with information tailored at a regional level.

Quantifying wind wave changes along Australia's coast

Wind waves are a type of wave created on the sea surface when the wind blows. They play a critical role in processes like coastal sediment transport and ocean–atmosphere heat exchanges. Climate change is driving changes to ocean surface winds and, in turn, wind waves, which is likely to contribute to future coastal flooding and erosion.

Through the Coordinated Ocean Wave Climate Projections (COWCLIP), Hub researchers used a new community-driven wind wave model ensemble to assess how wind waves may change in Australia and globally under future warmer climate scenarios.

The COWCLIP community developed over 150 simulations of future wind wave scenarios based on a high-emissions scenario. The projections indicate that the wind wave climate is likely to change in many coastal regions of Australia, particularly in the south, where there is likely to be a robust change in annual mean significant wind wave height and period (+5-15 per cent). These changes need to be considered in the context of other climate impacts, including any changes in frequency and/or intensity of storm surges, which can cause coastal erosion.

More accurate projections of wind waves will help coastal managers to understand the projected changes to key characteristics of wind waves, such as wave height, wave period or length and/or wave direction. This is useful in the context of engineering projects (e.g., construction of coastal structures), offshore activities or for planning shipping routes.

> **Equipping coastal managers with the knowledge they need to understand wind wave changes along Australia's coastline.**

■ Hub researchers studied how climate change will drive changes to wind waves under future warming scenarios.

ISTOCK.COM/AYAN MANDAL

Providing an improved picture of multi-year drought in Australia

Droughts can have devastating impacts on agriculture, the environment, lives and livelihoods. At any given time, many regions in Australia face water stress, but successive and long-lived droughts over multiple years could mean that some communities run out of drinking water.

In Australia's agricultural industry (currently worth around $60 billion per year to our economy) water is the most universally limiting factor in production systems. With so many end users of climate information in Australia all facing multiple pressures, managing drought is challenging enough but responding to this challenge is made more complex by a lack of consensus over what constitutes a 'multi-year drought'. This is partly due to a shortage of information on the factors that cause drought to persist.

Multi-year droughts broadly encompass droughts that last two or more years. Past studies have defined them in a variety of ways including repeated years of abnormally low rainfall, soil moisture or run-off, or when a drought metric is well below-average over a multi-year period.

Researchers at the Hub set out to build a more complete picture of multi-year droughts in Australia, bringing together 50 Australian and international experts in a workshop to discuss the current understanding of drought and identify knowledge gaps. One of the critical outputs of the workshop was reaching a common definition of a multi-year drought.

Multi-year droughts are not always completely dry. In any month, season or year, rainfall that is at, or even above, average can be recorded. Instead, the common characteristic of all multi-year droughts is the lack of substantial rainfall, that is, no periods with rainfall well-above average. High rainfall accumulations are necessary to recharge hydrological systems, even after a period of relatively short-lived dry conditions (e.g., multiple months or seasons).

Based on limited studies, climate models simulated under a high-emissions scenario suggest that multi-year droughts would be likely to become more frequent over the coming century in response to global warming. There are, however, continuing uncertainties in projecting the frequency of drought occurrence, and in understanding its varying lengths and sporadic nature. These uncertainties heighten the need for a more thorough understanding of the concept of multi-year droughts.

> **Identifying gaps in understanding multi-year droughts in Australia to improve preparedness and resilience.**

Understanding the risk of flash drought

From near-normal conditions to extreme drought in just a few weeks, flash drought seemingly comes from nowhere, with little warning or time for preparation. Vegetation dries rapidly, and crops and pastures wither.

With a focus on understanding when, where and why flash drought occurs, Hub researchers worked to identify the risk of flash droughts for Australia, and the tools most useful for monitoring them.

Research findings indicate that a flash drought is set in motion by lower-than-average rainfall, accompanied by abnormally high temperatures, a dry atmosphere, clear skies and more sunshine. Higher temperatures increase evapotranspiration (the evaporation of water from soil and plants to the atmosphere) and this 'thirsty' atmospheric state, in turn, lowers soil moisture, which is exacerbated as drought conditions continue. A positive feedback loop (a process that reinforces itself) is formed, perpetuated by dry and hot conditions and a lack of soil moisture. Flash drought is heralded by a critical point of decline in soil moisture that causes major stress for vegetation.

It is possible to measure these changes to evapotranspiration and soil moisture in indices like the Evaporative Demand Drought Index (EDDI), which captures the precursor signals of water stress at weekly to monthly timescales, and the Evaporative Stress Index (ESI), which describes anomalies in evapotranspiration over time, highlighting areas with anomalously high or low rates of water use across the land surface. Hub research found that the EDDI and ESI can capture flash drought as it develops, and are useful tools for flash drought monitoring.

Research from the Hub is also challenging our understanding of the timing and duration of flash droughts. While they are most prevalent during summer and autumn, findings indicate they can occur year-round, even during winter in southeast and southwest Australia. Likewise, the 'normal' duration of a flash drought is typically around a month, but the Hub's research shows that, in summer and autumn, some flash droughts have been the catalyst for longer droughts of six or more months duration.

Flash drought in the Wimmera region

Flash droughts in southeast Australia can have significant impacts on key pulse crops such as chickpeas.

The Wimmera region of southeast Australia experienced a flash drought in the spring of 2015. A persistent warm spell set in at the end of September, followed by a heatwave in the first week of October.

Immediately prior to the start of the flash drought, large changes in the EDDI and ESI occurred, highlighting the role that evaporative demand can play in flash drought.

Hub research into this event demonstrated the role of the EDDI and ESI in capturing flash drought, and their utility as tools for flash drought monitoring.

Helping agriculture and natural resource managers better prepare for flash droughts in the future.

■ Flash droughts in southeast Australia can have significant impacts on key pulse crops such as chickpeas. ISTOCK.COM/GRIGORENKO

Bushfires

Understanding future bushfire conditions under a changing climate

The Black Summer bushfires of 2019/20 devastated many communities in southeastern Australia. As much as 40 million hectares of Australia burned, over 30 people perished, billions of animals are thought to have been killed or displaced and there were massive environmental impacts.

Hub research has shown a clear link between climate change and worsening bushfire weather conditions over the past 70 years. This includes a trend towards more dangerous fire weather conditions in most regions, and an earlier start to the bushfire season in southern and eastern Australia. In spring 2019, information on the observed climate change trends, as well as future climate projections, was provided to state agencies, the Bushfire and Natural Hazards CRC, and the Australasian Fire and Emergency Services Authorities Council (AFAC) and their partner agencies. The information highlighted the increased likelihood of more severe conditions than ever previously experienced, particularly during spring and summer in parts of southern and eastern Australia. For managers of fire danger and first responders, this meant there was a clear need to prepare for worsening conditions in the future.

The Hub's bushfire research contributed to the Royal Commission into National Natural Disaster Arrangements following the Black Summer bushfires of 2019–20, and informed high-level briefings to government officials and the media. It has also been incorporated into climate change policies and statements.

Research on changing fire weather patterns will continue to inform decision-making by fire authorities, other emergency services and planning agencies.

> 'Having regard for climate and environmental science supports the emergency management sector's ability to take an informed approach to decision-making. The Hub helps support the sector's knowledge base and understanding of climate change in the context of increasing risk and uncertainty. It also assists in forming new conversations and initiatives that aim to provide the best overall environmental, social and economic benefit.'
>
> **– Luke Purcell, Manager, AFAC National Resource Sharing Centre Operations**

Providing authorities with advice on fuel reduction burns

Hub research found that, in many regions of southeastern Australia, windows for conducting fuel reduction burns are projected to decrease during the months currently used for conducting burns (March–May). In contrast, burn windows will generally increase in the winter months and further into spring (September–October). This change in seasonality means that these periods could be more suitable for conducting burns in the future.

Adding a new dimension to fire weather warnings

Quantifying the extremity of current bushfire conditions is critical information for fire agencies and emergency planning.

A common tool used by fire agencies to understand potentially dangerous weather conditions is the Forest Fire Danger Index (FFDI), provided through the BoM. The FFDI considers current temperature, humidity, wind conditions and recent rainfall but not historical conditions.

Hub researchers generated a new dataset of the FFDI so agencies could compare current bushfire conditions against historical data. This enables them to understand the 'big picture' of fire weather, and answer the question of just how extreme current conditions are.

During the summer of 2019–20, the historical dataset of FFDI (updated automatically each day) was used numerous times by authorities for guidance on the severity of conditions associated with the fire events. The ability to document and analyse conditions in this way helped enhance communication around the severity and anomalous nature of the conditions that were occurring.

With almost 70 years of fire weather data now available, researchers can use the dataset to identify and analyse long-term fire weather trends and relationships, including analysis of long-term regional trends. This supports the operational work of fire and emergency management agencies, and will inform our understanding of the climate changes already occurring, and those still to come.

Mapping spatial coverage of burnt areas

During the Black Summer bushfires, Hub researchers teamed up with international colleagues to produce a preliminary analysis of the spatial coverage of burnt areas.

Working with the Global Fire Emissions Database, and a consortium of research institutions including NASA and CSIRO, the Hub contributed to three satellite products, building a database of 32 years of fire frequencies and burn area, and allowing for multiple causal analyses using parameters such as moisture, the FFDI, and indicators of fire-generated thunderstorms and dry lightning frequency in the southeast. These products will enable further analysis into biomass and fuel accumulation change through Australia's land surface model, the Community Atmosphere Biosphere Land Exchange (CABLE).

Results showed that the burn area has increased over the past 32 years, and indicated that climate change is contributing to the increase. The analysis also accounted for interannual variability (such as the El Niño–Southern Oscillation, ENSO).

An increase in burn area has impacts on biodiversity and stored carbon in the landscape. Moreover, the increasing trends in burnt area are following the trends of fire weather indices, and provide the strongest multi-causal evidence to date that burned area in Australia has increased at least in part due to climate change.

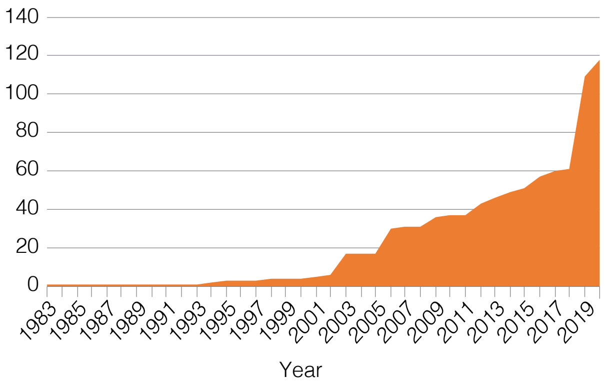
Future risks for fire-generated thunderstorms

The bushfires in Canberra in 2003, on Black Saturday in 2009, and during the Black Summer in 2019–20 were among the worst witnessed in southeast Australia in recent decades. All of these events triggered 'pyrocumulonimbus' fire clouds, where thunderstorms form in fire plumes.

In recent decades, fire-generated thunderstorms have been observed more frequently. Indeed, Black Summer produced about as many as were observed in the previous 35 years combined, showing how extraordinary that summer was.

Bushfires that generate their own thunderstorms are extremely dangerous. They increase the risk of erratic winds and unpredictable fire behaviour, such as the transport of burning embers and production of lightning that can ignite new fires far ahead of the fire front.

■ Cumulative observed number of fire-generated thunderstorms.
SOURCED FROM *DI VIRGILIO ET AL.* (2019) (UPDATED TO 2020).



Conventional fire-fighting is not effective when bushfires become so large and intense that they produce their own weather system. To enable more effective emergency preparation and management of future events, there is a need to better understand why, and how, fire-generated thunderstorms occur.

Hub research found that human-induced climate change has already influenced the frequency and severity of two risk factors that are associated with fire-generated thunderstorms: dangerous fire weather conditions near the surface (based on the FFDI), and conditions that allow smoke plumes to grow in height (C-Haines Index). An analysis of the FFDI and C-Haines values for historical fire-generated thunderstorms in Australia shows that they are more likely to occur when both of these indices are simultaneously high. Projections show a clear trend towards an increased risk of fire-generated thunderstorms for some regions of southern Australia.

Hub research also examined how non-fire-generated thunderstorm conditions have changed. Results show the trend is towards fewer thunderstorms but with more intense rainfall throughout most of Australia, and an increased frequency of dry lightning in parts of southeast Australia. Dry lightning (accompanied by relatively little rainfall) is a major cause of bushfires that can burn large areas of land in Australia.

These findings clearly signal more dangerous bushfire conditions for Australia in the future, and highlight the impact that further greenhouse gas emissions will have on the occurrence of these.

■ Fire-generated thunderstorms can produce extremely dangerous fire behaviour, with strong, erratic winds and lightning.

ALEX ELLINGHAUSEN

Climate variability and change

Australia is profoundly influenced by climate variability and climate change. Against a backdrop of variability, it has become increasingly clear over the past several decades that humans are having a direct impact on the climate. Most apparent are the physical impacts felt through extreme events including heatwaves, flood and drought.

To respond to future climate change impacts, there is a need to untangle the change in climate caused by humans from that of naturally-occurring climate variability. In some cases, it's about understanding the influence human-induced global warming has had on naturally-occurring patterns of variability such as the El Niño–Southern Oscillation (ENSO). The Hub has played a major role in advancing research on climate projections, climate model sensitivity and broad-scale climate variability.

Improving and advancing our understanding of ENSO and the Indian Ocean Dipole

Australia's climate variability is influenced by large-scale, coupled ocean–atmosphere climate modes including ENSO, Indian Ocean Dipole, (IOD), Southern Annular Mode, (SAM), monsoons and the Madden–Julian Oscillation, and their interactions.

In 2018 and 2019, a positive IOD coincided with a Central Pacific El Niño, which particularly affected Australia. Such a coincidence is rare, and had only been observed once since 1911, and it contributed to the extremely hot and dry conditions in the lead-up to the Black Summer bushfires. The average national FFDI in 2019 was the highest on record.

The Hub investigated the extreme positive IOD event of spring/summer 2019, which preceded the Black Summer bushfires. Results indicated that strong winds over the Indian Ocean, and the resulting air–sea interactions during the 2019 IOD event, were unprecedented, however, strong positive IOD events were likely to increase in frequency in the future. Hub research also showed, for first time, that strong El Niño events were projected to increase in amplitude and frequency under greenhouse warming. These findings point to the important role that reducing greenhouse gas emissions can play in the frequency of such extremes.

Untangling the relationship between climate phenomena and global warming sheds significant light on Australia's future climate. While extreme positive IOD events are projected to increase in frequency, the increase is also expected to stabilise if global mean temperature is kept below +1.5° C of warming. Unfortunately, even if the global climate was to be stabilised at +1.5° C, there is an increased risk of extreme El Niño events up to 2100. This means the severe droughts and bushfires observed over parts of southeast Australia in 2019–20 are likely to become more frequent.

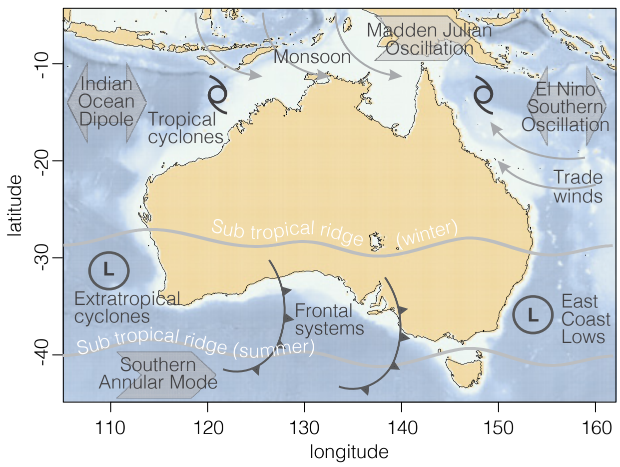
The ocean's role in climate variability

The ocean has a large influence on climate change, through storing and transporting vast amounts of heat and carbon dioxide (CO_2) as well as on climate variability through large-scale drivers such as ENSO. This influence extends from the coast to far inland, and affects us at timescales of weeks to centuries. ENSO, consequently, has a significant impact on Australia's climate, including rainfall, drought and extreme events, which makes it one of the most important climate drivers in our region.

Research from the Hub has improved our understanding of climate variability modulated by the oceans (including the ENSO, and the IOD), and attribution of longer timescale extremes such as drought. Using climate models to examine the interactions between tropical ocean regions and their impact on Australia's climate, Hub research revealed that tropical oceans are a tightly connected system, which includes strong feedbacks from the Indian and Atlantic oceans, onto the Pacific, and vice versa.

Improving the simulation of these feedbacks in climate models provides a pathway for improving predictions of climate variability in the current climate, and for refining projections of future climate. These improvements will provide decision-makers and managers with more accurate information about what our climate could look like in the future and how best to prepare for it.

■ Weather and climate drivers affecting Australia, from McInnes (2009).



Delving deeper, Hub researchers explored how interactions between the Indian and Pacific oceans impact various regions across the globe, and how these interactions may change in the future. For example, the research found that Indian Ocean short-term warming at the peak of a Pacific El Niño reduced the impact of the El Niño on air temperature across North Africa and South Asia. This demonstrates the extent of influence of Pacific and Indian ocean interactions, which occur against a backdrop of a long-term, rapid warming of the Indian Ocean, impacting large-scale and regional climate trends.

Experiments using the Australian Community Climate and Earth System Simulator (ACCESS), Australia's climate model, were also important in investigating the role of the South Pacific Ocean in modulating tropical Pacific Ocean variability. As the 'engine room' of ENSO, the tropical Pacific is recognised as particularly important to Australia's climate. On decadal timescales, a mode of variability called the Interdecadal Pacific Oscillation (IPO), which spans the North and South Pacific, modulates how ENSO impacts the Australian climate. For example, a cold phase of the IPO can mean an El Niño is more likely to affect Australian rainfall and surface temperatures.

Model simulations were used to quantify the impact of the South Pacific variability on ENSO and the IPO. With the IPO disrupted, decadal temperature variability in the tropical Pacific was reduced. Researchers also found that switching off the South Pacific reduced the extent of sea surface temperature variations during extreme El Niño and La Niña events.

This and other Hub research demonstrates that the climate processes originating in other ocean basins can have an impact on the magnitude of extreme ENSO events.

> **Improving Australia's climate preparedness by analysing modes of variability and improving climate models.**

■ Hub researchers have run attribution studies for high-profile events in the Australian region, which can help develop methodologies to underpin a future operational event attribution service in Australia.

Understanding the extent to which extreme events can be attributed to climate change

The warming of our climate due to human-induced greenhouse gas emissions is an unequivocal fact. Understanding exactly how climate change will impact Australia at a regional or local scale, however, is less clear. Some changes, such as sea-level rise, can be directly linked to past emissions that have caused an increase in global temperatures. Other climate changes, such as the increased frequency of heatwaves across Australia can be clearly linked to global warming, but for individual events in some regions, the links are less clear because of Australia's very large naturally-occurring climate variability. Understanding how climate change is affecting extremes can help us prepare for future extremes.

Hub researchers set out to tease out the impacts of climate change on the intensity of extreme events from those of naturally-occurring climate variability. Thanks to advances in the field of 'event attribution', including work by the Hub, researchers can now say with greater certainty whether, and by how much, climate change has contributed to the probability of some types of extreme events such as heatwaves on land and marine heatwaves, cold extremes on land, sea-level extremes, extreme seasonal fire weather, extreme one day rainfall and extreme high and low seasonal rainfall, occurring in Australia. While other types of extreme events currently have lower attribution confidence, event attribution studies could, in future, be extended to other types of extreme events such as tropical cyclones and hailstorms.

Assessing the extent to which climate change or naturally-occurring climate variability play a role in extreme events can now be done using large numbers of climate model experiments called 'ensembles'.

This involves running multiple experiments, using multiple possible versions of Earth's climate. Of the many possible 'worlds' represented by each experiment, researchers quantify the probability of the event occurring in the 'world as it is' (with human influences on climate) and 'the world that might have been' (without human influences on climate). The results show the increased or decreased probability of such an extreme event occurring due to climate change or natural variability.

Hub researchers have run attribution studies for high-profile extreme events in the Australian region. For example, the reduced rainfall over Tasmania in 2015 carried the signal of climate change. Conversely, the extreme rainfall event in the Murray Darling Basin in September 2016 was dominated by natural variability, and the signal from climate change was not clear.

Hub research in event attribution can help develop methodologies to underpin a future operational event attribution service in Australia; a new capability that would be of huge significance. It means we could assess the extent to which damaging events are linked to climate change and, in doing so, improve our understanding of the current impact of climate change and our preparedness.

Moreover, event attribution can now be performed as a rapid analysis, providing a near-real time tool for understanding the role of climate change in an extreme event.

> **Providing the underpinning science for a future operational climate event attribution service in Australia.**

Case study:

A rapid analysis into high temperature records and climate change in Australia

When high temperature records are broken, a common question asked of climate scientists is, 'what role did climate change play in this event, and what was the role of natural climate variability?'

Spring (September – November) 2020 and the month of November 2020 in Australia set new record high temperatures averaged across the country.

Rapid analysis assessments, which can be conducted in as little as two days, are helping to better quantify the contribution of human-induced climate change.

By teasing out the contributing factors of background warming and climate variability, these assessments provide a new tool for researchers to foreshadow other extreme events and help decision-makers prepare.

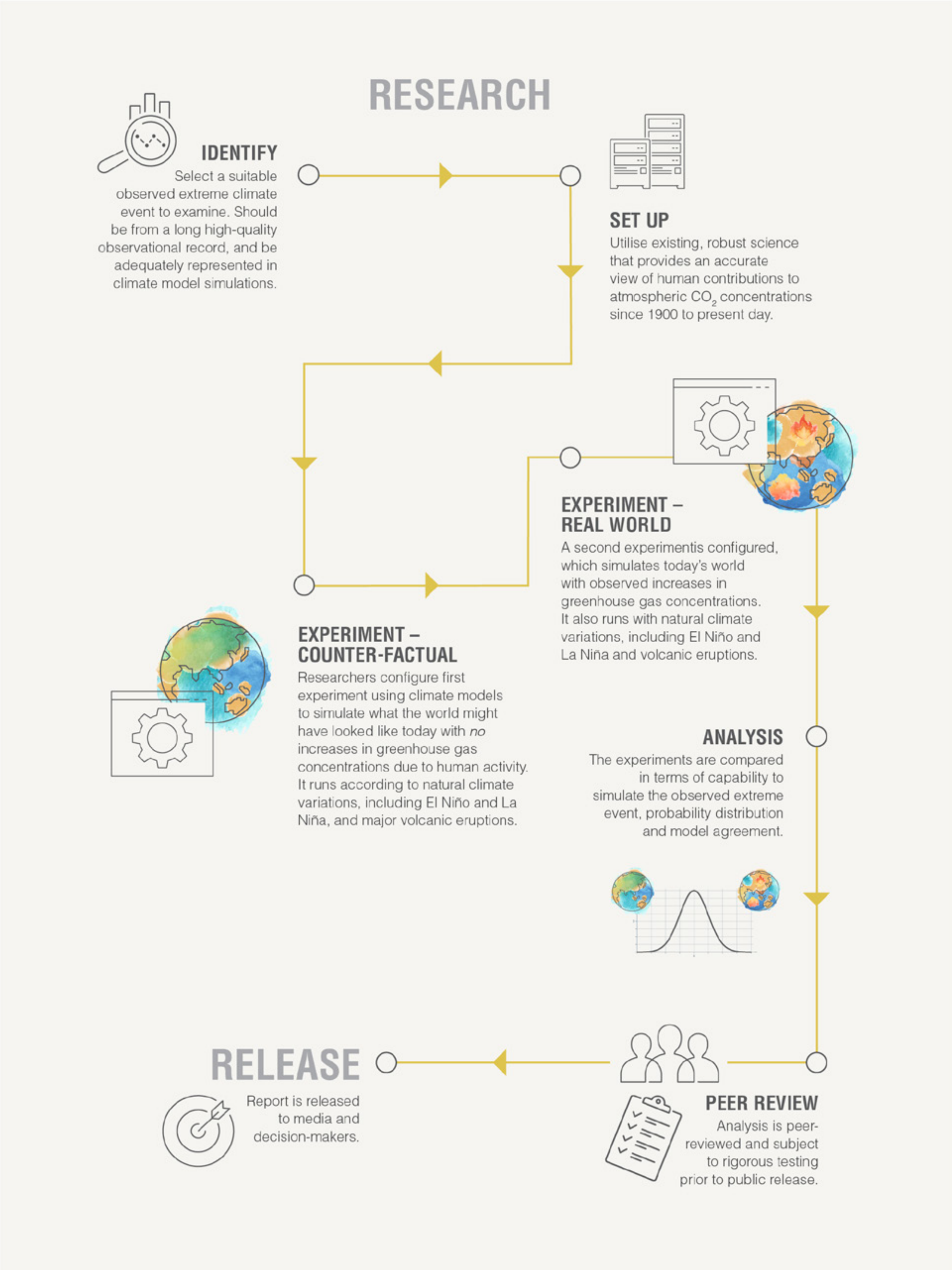
Building on existing studies conducted on 'extreme event attribution', in the Hub and through Australian universities, Hub researchers undertook a rapid analysis into the record-breaking temperatures of spring 2020 to isolate the roles of accumulating greenhouse gases in the atmosphere and large-scale climate patterns including ENSO.

The analysis involved a comparison of the Australian average spring temperatures simulated by global climate models. Results revealed that the record 2020 spring temperatures across Australia were virtually impossible due to natural climate variability alone. The extreme temperatures were mainly a result of the background warming trend associated with higher greenhouse gas concentrations in the atmosphere.

The research also found that the record-breaking temperatures were reduced by the developing 2020 La Niña event, which is normally associated with colder-than-average temperatures.

This example of rapid analysis shows the potential for near real-time information on climate change that can be made available to the public, as well as policy and decision-makers.

■ **Extreme event attribution.** An outline of the methodology used for Hub rapid analysis assessments in extreme event attribution.



Coasts and oceans

The ocean is an important part of Earth's complex and variable climate system. It is the largest sink on Earth, absorbing and storing heat, nutrients and CO_2. Climate change is altering the nature of our oceans and impacting the way the ocean influences Earth's weather and climate. Research from the Hub has provided new insights into the role of the ocean in the climate system. These observations, models and assessment studies have laid the foundation for more reliable predictions and projections of severe climate event felt most acutely at our coastlines, including global and regional sea-level rise, marine heatwaves and coastal erosion.

ISTOCK.COM/MYFANWYJANEWEBB

Developing an integrated view of the Earth's ocean monitoring

Observing and measuring ocean parameters is vital for managing and mitigating human impacts on our environment, understanding weather patterns and making climate and weather predictions. High-quality ocean observations of temperature, salinity, carbon and other variables enable key research into ocean variability and change.

The ocean extends far beyond any national boundary, so international collaboration and coordination is a vital but challenging task. The Hub supported Australian participation and leadership in national and international ocean observing systems and initiatives, helping to better understand our changing oceans.

Australia has provided leadership in the generation of high-resolution ocean datasets, which are relied on by the research and wider communities. It also led the international community in quality control procedures, implemented in international collaborations like Argo, XBT and GO-SHIP programs. The resulting high-quality products have become the go-to resource for all prominent global re-analyses (the equivalent of national meteorological forecasts for the oceans), and also form the basis of all gridded ocean data products such as the World Ocean Atlas (National Oceanographic Data Center, USA).

Australian participation in these activities has been vital for the coordinated creation of the ocean information that underlies forecasting and information for researchers, decision-makers and the Intergovernmental Panel on Climate Change (IPCC) assessments (including the recent IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate,* SROCCC*).*

> **Enabling access to information on ocean change and climate variability for international climate assessments.**

A global observation system to understand future ocean heat uptake

Oceans play an important role in the Earth's climate system. They have a much greater mass and capacity to absorb heat than the atmosphere, and have absorbed more than 90% of the excess heat in the Earth system created by global warming. This has slowed the rate of warming in the atmosphere, limiting the damage to land dwellers, but has led to warmer oceans and sea-level rise.

As Earth continues to warm and our climate is further disrupted, one key area of research is to understand the processes that drive ocean heat uptake, and how that uptake may change in the future.

Hub research has contributed to improving the national and global ocean observation system. This, in turn, has enabled integrated monitoring of ocean heat increases, including how heat is distributed throughout the ocean depths and across the globe, and how it is changing over time. The ocean distributes heat absorbed at its surface unevenly, so it is important to understand the different rates of warming in different regions. For example, the Tasman Sea has been warming four times faster than the average global rate of warming.

Hub researchers used data collected from ocean monitoring (historical archives, Argo floats, XBT and research vessels) to create a combined dataset that included ocean profiles collected as far back as 1772. This high-quality dataset provides an in-depth view of ocean parameters over time and will enable, for example, research to examine the connection between ocean salinity changes and rainfall across Australia. The dataset is delivered to a broad community of users in Australia and overseas. Importantly, it is delivered in an 'analysis-ready' format, which means it can be used to inform further scientific research into our changing oceans, and underpin critical climate assessments, including those by the IPCC.

Improved ocean observations support a host of research and mitigation and adaptation activities. They provide data on initial conditions for seasonal-to-decadal climate prediction systems, monitor and detect ocean change, assess variations in sea-level and contribute to climate model evaluation and development.

In addition to supporting further research, improved ocean observations can also meet the growing demand for weather and ocean services and forecast products, multi-hazard early warning systems and climate and ocean health applications.

> **Improving our understanding of past and projected changes to the temperature of Earth's oceans through international collaboration.**

Understanding regional variations in ocean heat content

The southern hemisphere contains 63 per cent of the Earth's oceans. Together, these account for 67–98 per cent of the total increase in ocean heat globally (in the upper 2000 m of the ocean).

That's not to say that all oceans in the southern hemisphere are warming at the same rate. In fact, Hub research found that surface waters close to Antarctica have actually cooled, despite overall warming of the atmosphere. Surface water cooling is, in part, caused by the release of fresh water from melting ice, which can cool the surface layer but warm the subsurface waters in ice shelf cavities.

This and other research from the Hub on the Southern, Pacific and Indian oceans has been critical in the detection and attribution of the magnitude, distribution and cause of ocean heat change. The Hub's contribution to high-quality ocean observations has enabled researchers to understand why heat is redistributed unevenly in oceans, and why some parts of the southern hemisphere oceans have been warming faster than the global ocean.

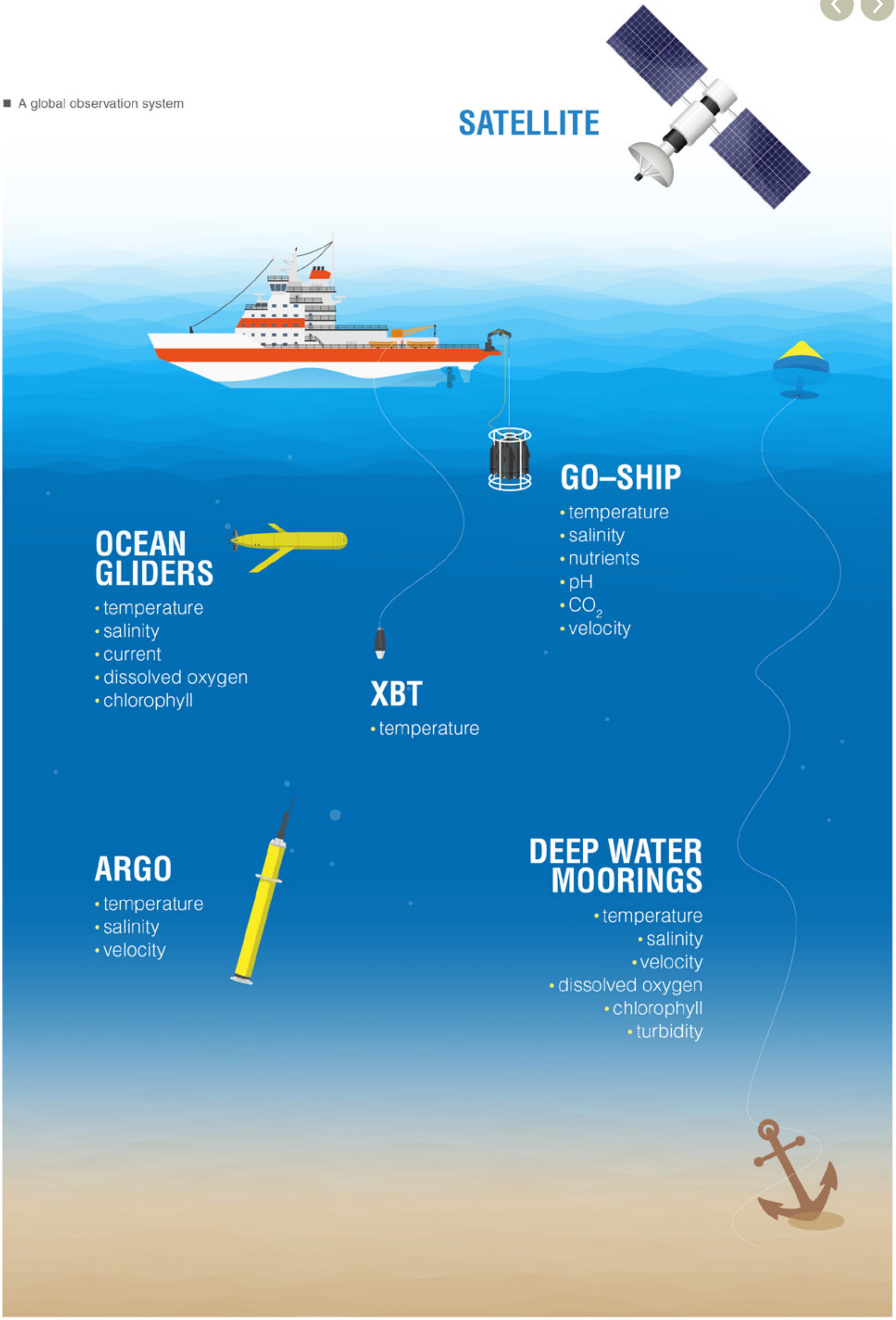
The research identified a pattern of variability in ocean heat content, called the 'Asymmetric Mode' (AM), which is independent of global warming and other well-known modes (such as ENSO, IOD and SAM), and existed prior to the onset of global warming. The AM represents a global-scale shift in ocean warming between hemispheres that occurs over decades. But the dominance of southern hemisphere warming appears to be waning, which means rates of ocean warming may soon increase in the northern hemisphere.

The southern hemisphere oceans are a major driver of the weather systems across the entire planet, with the heat gained in the Southern Ocean circulating into the Indian, Pacific and Atlantic oceans. Improving our understanding of the underlying mechanisms of heat distribution, and regional variability, is therefore of critical importance.

Findings from the Hub's research provided input into major international assessment reports including IPCC assessment and special reports, the annual World Meteorological Organization's *Statement on the State of the Global Climate* reports, the CSIRO/BoM *State of the Climate* reports, and the Australian Government's *State of the Environment* assessments.

> **Providing valuable insight and input into ocean heat uptake for international and national climate and ocean assessments.**

■ A global observation system



Case study:

Nature-based methods for coastal hazard risk reduction

Rising sea-levels due to human-induced climate change are contributing to accelerated erosion and flooding along Australian coastlines, with consequences for coastal infrastructure, communities, ecosystems and tourism.

Engineering solutions, like sea walls and breakwaters, are an increasingly costly and ecologically-damaging strategy to reduce impacts on the built environment. Artificial structures are not designed to last indefinitely, and need to be upgraded and replaced over time to continue to function, particularly following severe storm events.

Natural ecosystems, like oyster reefs, mangroves and salt marshes have been shaping up as promising alternatives. By acting as a buffer against waves and reducing wave height, these nature-based solutions demonstrate potential success in mitigating the impacts of coastal flooding and erosion. They can also accrete and stabilise sediments.

Unlike artificial structures, which need to be upgraded and rebuilt over time in order to continue to function, natural coastal habitats or 'living shorelines' (those created or restored for coastal protection), can adapt and self-repair by either growing higher or spreading. Living shorelines also have a number of co-benefits including enhanced biodiversity and improved surrounding water quality. Mangroves, seagrasses and saltmarshes also have great potential to sequester carbon in living tissue and in the underlying sediments, which is why some living shorelines are also referred to as 'blue carbon ecosystems'.

The National Centre for Coasts and Climate (NCCC), established through the Hub, set out to improve knowledge and resources on blue carbon ecosystems, coastal erosion and 'eco-engineering' coastal defence solutions. This included understanding the role of different natural habitats in reducing wave energy at specific locations on the Victorian coastline, and testing the hybrid coastal protection solutions in Port Philip Bay. Researchers also conducted a survey of Victorian coastal residents to understand the socio-economic barriers preventing the wide use of these nature-based coastal protection methods.

One substantial output from the research was a set of guidelines developed by the NCCC. *The Australian guide to nature-based methods for reducing risk from coastal hazards* represents the first comprehensive guide to nature-based methods that are specific to Australian systems. The guidelines summarise the physical processes that underpin nature-based methods, and the ecological and engineering considerations that apply for major coastal ecosystems found in Australia. Moreover, the guidelines provide a practical tool that can be used by coastal practitioners to support decisions on using nature-based methods for coastal protection.

While nature-based methods of coastal adaptation in Australia are in their infancy, there's now improved confidence that they can provide more climate-resilient coastal protection outcomes, particularly for certain areas of Australia's coastline.

Enhancing the resilience of coastal ecosystems and communities in order to protect Australia's coastlines.

'The connections and networking opportunities provided by the Hub have opened lines of communication between practitioners working in local government, scientists and researchers. This has generated links between all levels of government, institutions and stakeholders.
It has streamlined information, data exchange and the provision of advice.'

– Ralph Roob, City of Greater Geelong

■ Natural ecosystems, like oyster reefs, mangroves and salt marshes have been shaping up as promising alternatives to artificial structures like sea walls and breakwaters.

REG RYAN

Preparing Shark Bay for a changing climate

Home to red, weathered soils and turquoise waters, it's little wonder that Shark Bay in Western Australia topped the criteria to be recognised as a World Heritage Area (WHA) in 1991. Among its exceptional natural features are extensive seagrass beds stretching over 4000 km^2. It also contains some of the oldest lifeforms on Earth: numerous living stromatolite deposits, the layered biochemical accretionary structures that are formed in shallow water when microbes trap, bind and cement particles to create sediments. The WHA is home to Malgana Traditional Owners, and is famous for its rich marine life including sharks, dugongs, rays, dolphins and turtles.

Shark Bay's vulnerability to climate change is well recognised but it was pulled into sharp focus in 2010–11 when the Bay was affected by a marine heatwave, which resulted in the loss of 900 km^2 (or 36 per cent) of its large, temperate, meadow-forming seagrasses. While the impacts do not appear to have affected resident dugongs, long-term impacts were seen in dolphins (lower birth rates), and negative effects on nearby fisheries and low tourism visitation were also observed.

In 2018 the Hub participated in a workshop, facilitated by the Shark Bay World Heritage Advisory Committee (SBWHAC), to identify the possible impacts of climate change on Shark Bay. The aim was to provide the basis for development of a climate change adaptation strategy and action plan for the Shark Bay WHA, using a rapid assessment tool.

The Hub provided the climate change projections for Shark Bay and assisted the World Heritage Property Committee in understanding climate change impacts across the system. Hub researchers participated in the Climate Vulnerability Index activities and prepared the report for the workshop, which identified the impacts that could potentially affect Shark Bay's value as a WHA.

The research was presented to the SBWHAC, with support from the Western Australian Marine Science Institution, for implementation of the plan and development of an appropriate science plan. The findings of the report were also used by the International Union for Conservation of Nature in its 2020 Conservation Outlook.

> **Building the foundations for a climate change adaptation strategy and action plan in the Shark Bay WHA.**

■ The Hub helped to identify the possible impacts of climate change on Shark Bay.

The role of variability and underlying drivers of coastal erosion

When coastal erosion events occur they can be front-page news. Even if protective measures have been put in place, large swells and storm surges can force the evacuation of communities, cause the partial or total collapse of homes, and leave residents facing months to years in the recovery process.

Such events are happening around the world due to waves and storm surge and are compounded by rising global sea-levels. These threats to coastal infrastructure are predicted to increase as a result of climate change. The ever-increasing human population living near the coast is adding to this challenge.

Erosion is a primary concern for all coastal managers, and there is a growing need to consider coastal management options to limit damage from inundation events. Knowledge gaps remain, however, particularly regarding the amount of long-term shoreline retreat that may occur under climate change.

Hub research, conducted through the NCCC, investigated the causes and underlying drivers of coastal erosion, and how climate change is likely to impact future erosion. This included quantifying historic shoreline changes in Victoria, examining changes to beach and dune morphology as a result of erosion, and the role of vegetated systems (coastal dunes) in mitigating erosion.

A further collaboration between researchers at the NCCC and the Hub looked at Ninety Mile Beach in East Gippsland, Victoria. The case study, conducted through field surveys and models, explored the shape of foredunes in the area and found the main cause of shoreline change since 2007 was a long-term decline in the amount of sand stored in the dunes. The continued decline in stored sand will likely reduce the protective capacity of coastal dunes in the future.

> **Providing coastal managers with information to assist them in protecting coastal communities and infrastructure from severe wave damage.**

■ Erosion and house damage immediately after the storm.
WATER RESEARCH LABORATORY, UNSW

Supporting the understanding of climate adaptation in Tiwi Island communities

Adaptation to sea-level rise and coastal erosion in the Tiwi Islands is paramount given the ongoing nature of climate change. Impacts from inundation include damage to power and communications infrastructure, and to settlements from storm surge and flooding. In the face of these damaging events, the need to adapt to climate change can often evoke feelings of hopelessness rather than inspiration. Despite this, practical and empowering responses can play a key role in helping communities act on their goals and values for the future.

Working with the Tiwi Land Council, the NCCC and the Hub supported engagement activities to discuss climate adaptation with local communities. A subsequent report provided the foundation for working with Tiwi Islanders to develop practical guidelines for monitoring and adaptive management of coastal erosion.

Case study:

Contributing to world-leading assessments of climate change

The IPCC provides governments across the world with scientific information that can be used to develop climate policies. Its assessment reports cover the scientific basis of climate change, its impacts and options for adapting to future risks or mitigating the causes of climate change.

The IPCC is one of the most trusted sources of climate science information, with its evidence-based reports recognised and used for policy and management decisions by governments and organisations, globally.

Testament to the Hub's world-class science, researchers from the Hub were contributing authors for the recent high-profile IPCC report, SROCCC, which received widespread international attention.

The SROCCC noted that global sea-levels are rising approximately twice as fast as 20th century averages, and that the oceans are heating twice as fast, absorbing more carbon and acidifying in the process.

Hub researchers contributed to a chapter that outlined the impact of warming and acidification on oceans, and the cascading impacts on weather and marine life ranging from phytoplankton to marine mammals. Researchers also reported on the range of impacts to coastal ecosystems, including contracting distributions of seagrass meadows and kelp forests, and the increased frequency of large-scale coral bleaching events. The chapter explored the various impacts on different stakeholder groups including fisheries managers, whose livelihoods are challenged by lower productivity in fish stocks, and highlighted the need for timely mitigation and adaptation responses.

Researchers from the Hub also led a chapter examining the impact of climate change on compound events and cascading impacts. Case studies in this chapter emphasise how compound events, such as the 2015–16 summer in Tasmania, stress the capacity of both society and the environment to respond and rebound. During this period, a marine heatwave off the coast of Tasmania coincided with bushfires and floods, together with a prolonged drought. These extremes and compound risks are projected to become more frequent and/or more intense due to climate change.

Results from the SROCCC report were shared with Hub stakeholders and were presented at the United Nations Climate Change Conference (COP25), the leading international meeting for climate change policy and development.

Hub researchers are lead and contributing authors for the IPCC Sixth Assessment Report (IPCC AR6). This affirms the significant contributions to the international climate science effort made by Hub researchers and their recognition as leaders in the field.

Contributing scientific authorship to international climate change assessments that can inform policy and mitigation planning.

■ The results from the SROCCC report were shared at the United Nations Climate Change Conference (COP25).

IISD/ENB/MIKE MUZURAKIS

Indigenous science

First Nations peoples in Australia have been responding to climate variability and environmental change for millennia, and have a lot to teach us about caring for Country.

With climate change threatening Country and communities, First Nations' organisations need the best-available climate change science to supplement traditional knowledge and help them care for the land in a changing climate.

Collaboration between First Nations peoples and the Hub has resulted in innovative ways of developing and using climate change science to make it relevant and accessible to all peoples. A co-design process has underpinned much of this work, and has helped the Hub build strong relationships with stakeholders that will benefit future climate adaptation projects.

Understanding Indigenous perspectives on climate risk

Many First Nations peoples reside in remote and highly-vulnerable environments, where climate change impacts on their Country and culture are already evident. These include increasing extreme weather events, rising temperatures and sea-level change. Understanding how climate change is likely to affect First Nations peoples and communities is important information for future planning.

The current and future climate change impacts are compounded by overarching socio-economic disadvantage and chronic health conditions affecting First Nations peoples. The social and cultural burden of historic colonial dispossession adds a further layer of complexity.

Consequently, First Nations peoples often bring a particular perspective of risk that is specific to their communities and cultures. The Hub worked with First Nations peoples in a two-way sharing of climate knowledge that will contribute to place-based risk strategies.

> **Tailoring climate change information to differing perspectives to help improve the participation and inclusion of First Nations people in climate planning.**

Understanding climate change impacts on Torres Strait fisheries and marine ecosystems

In the Torres Strait the impacts of climate change are already observable – from coastal erosion and increasing sea surface temperatures to reef health decline.

Rising sea-levels are driving increasingly frequent tidal inundation events that affect communities, ecosystems, infrastructure, livelihoods and wellbeing. With long-term projections of global sea-level rise reaching 0.8 m by 2100, rising seas threaten to displace whole communities.

As an island-based region heavily dependent on fisheries and marine resources, these communities are especially vulnerable to climate change and need to be prepared for future changes. Communities, including Traditional Owners, are keen to be involved in discussions and associated decision-making.

The Hub partnered with the Torres Strait Regional Authority to bring together Torres Strait Traditional Owners, fisheries managers and scientists for a technical workshop to discuss the implications of climate change on fisheries management in the Torres Strait. The workshop was co-designed with the Torres Strait Regional Authority to ensure industry leaders are able to take climate change information and use it in their adaptation planning processes.

> **Torres Strait commercial fishery industry has a better understanding of the impact of a changing climate on the industry.**

■ Rising sea-levels in the Torres Strait are driving increasingly frequent tidal inundation events that will have implications on fisheries management.

Meeting Indigenous priorities for collaboration in climate change science and engagement

There is a long history of First Nations peoples in Australia collaborating with scientists and academic researchers and, currently, there are many climate change conversations regularly occurring with First Nations groups and partners across Australia.

Historically, however, many of these discussions have been, and are still often, considered problematic. Many have been limited by a lack of two-way knowledge exchange, for example, not obtaining free and prior consent from Traditional Owners, or a lack of follow-through with provisioning of intellectual property ownership.

Other barriers to empowering First Nations peoples with climate change information have historically included communication between First Nations peoples, scientists and policymakers. Climate change projections are not easily understandable beyond the academic community, and they are not necessarily related to people's personal experiences on Country. This makes it difficult to communicate climate risks to local communities.

The Hub has taken significant steps in overcoming these barriers and building sustainable partnerships. As part of the Australian Meteorological and Oceanographic Society (AMOS) conference in Fremantle in February 2020, the Hub convened a workshop to discuss how researchers and First Nations peoples should collaborate on climate change information and science.

Participants at the workshop identified a series of important considerations for co-design approaches to research projects, on climate change and more generally. These included ensuring Traditional Owners were included from the start (and subsequently), and respecting the provision and ownership of traditional knowledge. Co-design principles developed in the workshop, and rolled-out throughout the Hub, highlighted the need for researchers to improve their inclusion of Traditional Owners in research inception, development and delivery, with a view to mutually useful and usable research outputs.

The co-design principles were further developed with the Steering Committee of the National First Peoples Gathering on Climate Change 2021, with the intention of incorporating these in the 2021 event and ensuring the event itself was co-designed.

> **Building sustainable partnerships with First Nations people to develop co-design guidelines for climate change collaboration.**

Case study:

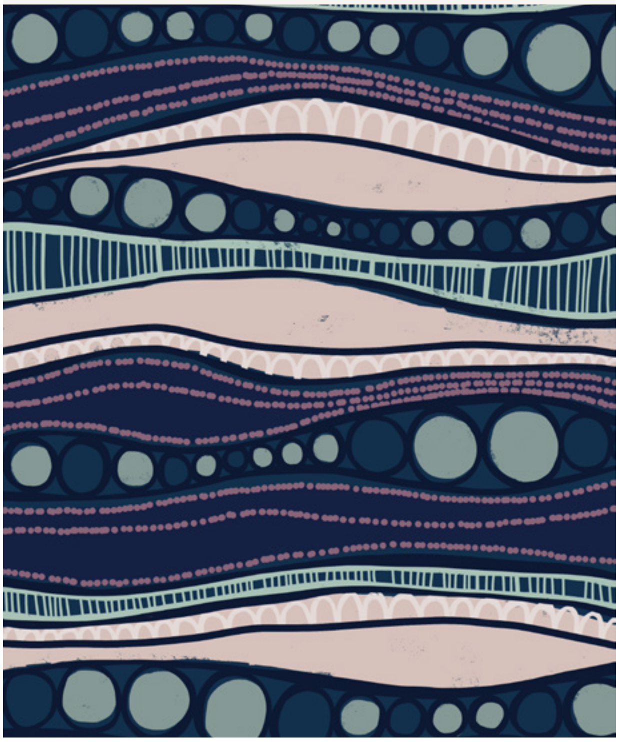
Empowering Indigenous participation in the national climate change dialogue

The benefits of bringing First Nations' and climate science knowledge systems together to develop innovative solutions for environmental and climate change problems are obvious, however, the steps to do so are not.

To support ongoing collaboration and a two-way understanding of climate change, the Hub convened two on-ground events, intended as a knowledge exchange. The aim was to develop a better understanding of First Nations people's priorities, build capacity and enhance engagement with First Nations communities.

Feedback from participants confirms that breaking down barriers through face-to-face interactions can significantly empower First Nations peoples, and promote knowledge sharing about the best way to care for land and sea Country.

These engagements have reinforced the need for the intellectual and cultural property rights of First Nations peoples to be embedded in ongoing co-design elements. Future initiatives including through the Climate Systems Hub will continue to build on this important work.



■ Layers of Country by Keisha Leon.

National Indigenous Dialogue on Climate Change (2018)

The Hub worked with the Yorta Yorta National Aboriginal Corporation (Yorta Yorta) to co-design a gathering to discuss First Nations people's priorities for climate change. The National Indigenous Dialogue on Climate Change was hosted by Yorta Yorta Traditional Owners on their ancestral Country at the Dharnya Cultural Centre in Barmah, Victoria in November 2018, and facilitated through the Hub. It was planned with assistance from a First Nations-led Steering Committee that included the co-hosts from Yorta Yorta, the Kimberley Land Council and the Indigenous Youth Climate Network.

More than 50 Traditional Owners from across Australia came together to talk about climate change; sharing their observations, identifying their priorities, and exploring opportunities to improve knowledge of climate change and its risks for people and Country.

Importantly, the two-way dialogue between researchers working on climate change and Traditional Owners helped to improve the understanding of mutual goals and potential benefits from working together to support the community's climate information needs. This dialogue was documented in a co-authored report from the workshop.

The Indigenous Dialogue generated a strong response among First Nations peoples and communities across Australia. Indeed, it has been noted as one of the most significant national gatherings of First Nations people on climate science research priorities, and highlighted the importance of an ongoing dialogue.

Several priorities for future research were also identified including bio-cultural renewal, monitoring of seasonal indicators, impacts on water cycles/flows, water rights and access, impacts of resource extraction, governance and institutional responses, cumulative impacts and many others.

National First Peoples Gathering on Climate Change 2021

The National First Peoples Gathering on Climate Change 2021 was held in Cairns over 5 days from 22 to 26 March.

Gimuy Walaburra Yidinji and Yirrganydji Traditional Owners from the Cairns region embraced 120 guests on their Country with a warm and celebratory welcome. Yorta Yorta Traditional Owners also formally handed over the ceremony proceedings to Gimuy Walaburra Yidinji and Yirrganydji hosts.

Over the ensuing days participants shared climate change knowledge and experiences through a series of co-designed sessions. Facilitated by Traditional Owners and scientists, they covered topics ranging from extreme heat, extreme water events both wet and dry, to sea-level rise, tropical cyclones, marine heatwaves and bushfires.

The Gathering allowed participants to share knowledge as well as co-design and develop adaptation and mitigation strategies.

The 2018 statement was revised in line with feedback from participants and is scheduled for publication in 2021.

'To pull off an amazing event like we had in Cairns is a true testament to each one's commitment to ensuring that Traditional Owners could come together with western Scientists, modellers and researchers to learn from each other about climate change and the challenges we all face together.'

– Damian Morgan-Bulled, Co-Chair, NFPGCC Steering Committee.

Facilitating a two-way dialogue between researchers and Traditional Owners to improve knowledge of climate change and its risks for people and Country.

The National First Peoples Gathering on Climate Change 2021 brought together Traditional Owners and climate scientists to share climate change knowledge and experiences.

Global and regional carbon budgets

Stabilising the climate at +1.5° C above pre-industrial levels and 'well below' +2° C to meet the target of the Paris Agreement requires CO_2 emissions to reach net zero. Limiting future global climate change requires a substantial and sustained reduction in net greenhouse gas emissions. Tracking progress towards global targets, including the Paris Agreement, requires data on the amount of CO_2 that is being emitted from human-related sources (and from where). It also means we need to quantify the extent to which land and ocean-based sinks are taking up CO_2.

Carbon budgets, which provide data and analysis for both natural and human-related sources and sinks of CO_2, are playing an increasingly important role in informing mitigation policy responses around the world.

Developing a global carbon budget

Since 2016 the Hub has supported the ongoing development of the *Global Carbon Budget*, a report produced annually by the Global Carbon Project. It is key research that attempts to close (or completely account for) the entire global budget of human-related and natural sources and sinks of major long-lived greenhouse gases including CO_2, methane and nitrous oxide.

The *Global Carbon Budget* assesses the ability of ocean and land sinks in sequestering CO_2, and carefully accounts for uncertainties in each source and sink. This methodology allows for tracking of global emissions progress towards the targets of the Paris Agreement. However, since 2015 and until the COVID-19 pandemic, human-related emissions of CO_2 had grown by around 4%, further increasing the challenge to stabilise global warming at that level.

Research underpinning the *Global Carbon Budget* has progressed the scientific community's understanding of the uptake of CO_2 by natural sources and sinks. Rising atmospheric CO_2 levels increase the uptake of CO_2 by the oceans and land. In the ocean, this affects carbonate chemistry and decreases pH in a process known as ocean acidification. Ocean observations, including those analysed by the Hub, have shed light on feedbacks in the system and the rate at which ocean sinks can remove carbon.

Further model development, including work conducted with the Australian land model CABLE, has also improved our understanding of the terrestrial carbon cycle, or more specifically, the exchange of CO_2 between the atmosphere and land-based vegetation.

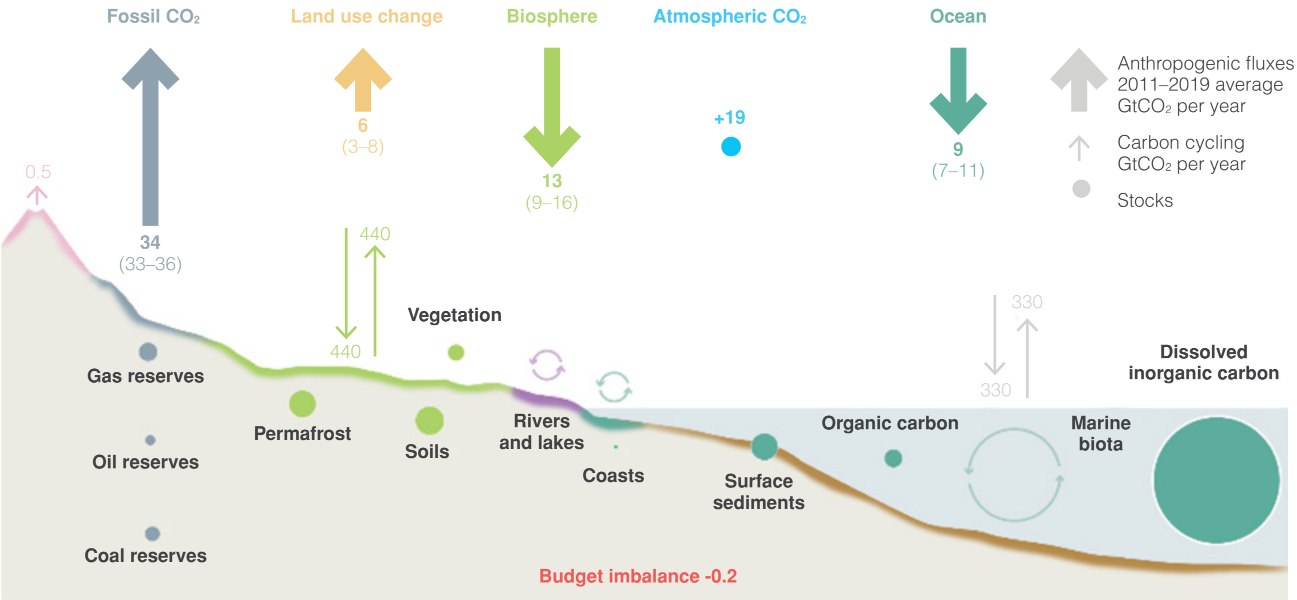
Global carbon budget accounting has improved over the lifetime of the Hub, with significant contributions from Hub researchers. This is thanks to an improved understanding of the sustainability of nature-based solutions under a changing climate, such as carbon sequestration through blue carbon ecosystems, increased revegetation (planting of more trees) and First Nations' cultural burning activities.

Changes in land management such as land clearing and revegetation lead to human-induced increases in CO_2 emissions and sinks, respectively. The *Global Carbon Budget* has also enabled important research into the impact of land management practices and showed, for the first time, that emissions from land clearing are about double (17 gigatonnes CO_2, or $GtCO_2$) than the previously reported net land use emissions (7 $GtCO_2$), with an additional large CO_2 sink (11 $GtCO_2$) from natural and human-induced forest generation.

Providing a holistic view of the land– and ocean–atmosphere exchange alongside human-induced carbon emissions and sinks puts human-related emissions into perspective for policy-makers and the community alike. The IPCC now relies on the annual *Global Carbon Budget* reports to provide the carbon budgets for its assessment reports.

The construction of the *Global Carbon Budget* is only possible because of the scientific and data contributions of 68 research institutions from around the world. While the annual *Global Carbon Budget* focuses on global emissions and sinks, it also includes regional and some national breakdowns, including Australia's carbon budget, which is led by the Hub.

■ **Perturbation of the carbon cycle caused by anthropogenic activities.** Anthropogenic fluxes of CO_2 measured in $GtCO_2$ per year, averaged globally for the decade 2010-2019. The budget imbalance is the difference between the estimated emissions and sinks. Source: CDIAC; NOAA-ESRL; Friedlingstein et al 2020; Ciais et al. 2013; Global Carbon Budget 2020.



Case study:

Communicating the scale of the impact of COVID-19 on the remaining carbon budget

From global confinement measures for weeks at a time to the temporary shutdown of global transport and industry, the COVID-19 pandemic presented an opportunity for analysis into the scale of the human-induced contribution to global CO_2 emissions.

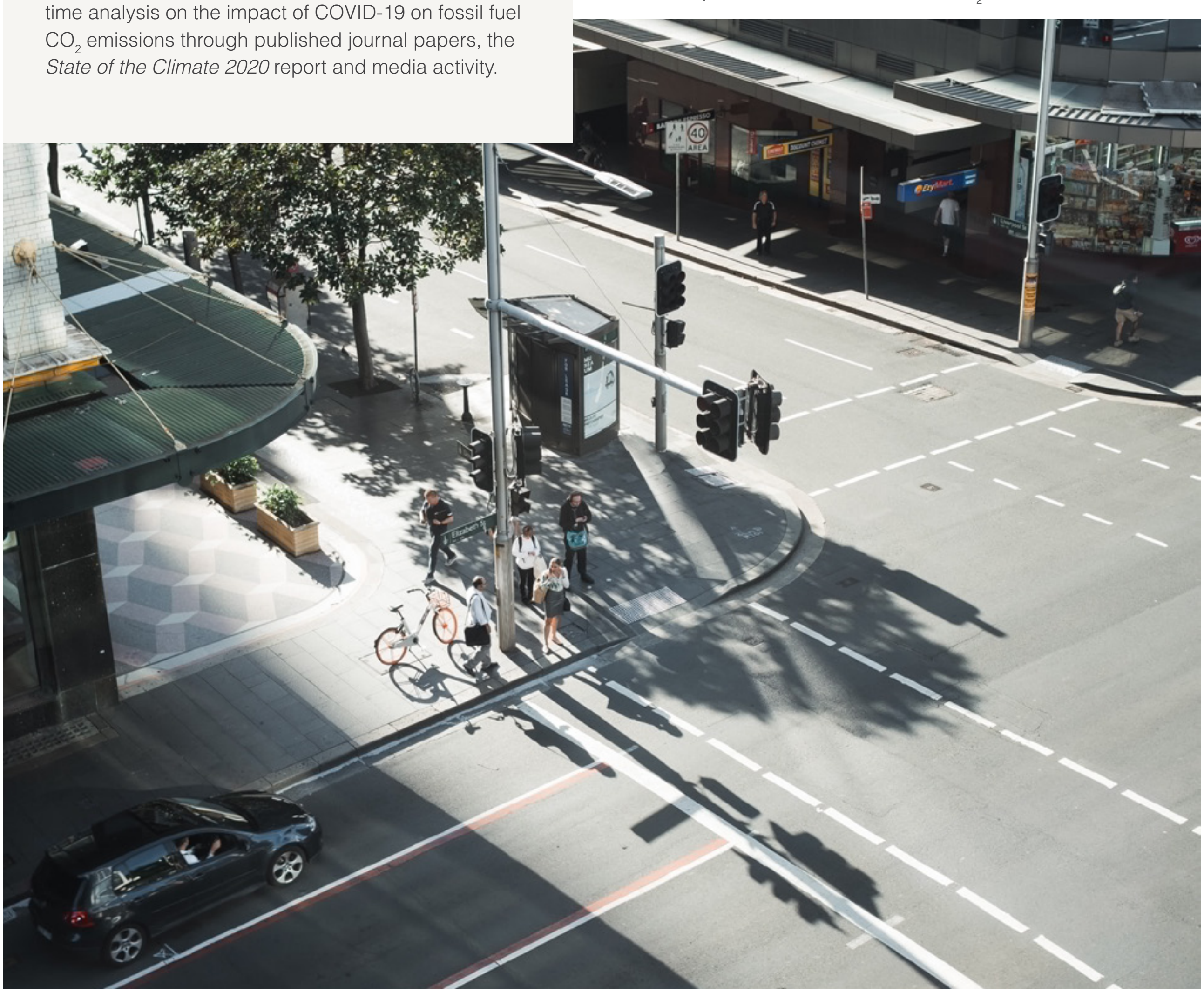
Early in the COVID-19 pandemic, media coverage reported citizen observations of improved air quality levels. Reduced air travel and passenger car transport due to travel restrictions led to questions on the impact of the COVID-19 pandemic. Did it cause human-induced greenhouse gas emissions to drop? And did the upwards trajectory of CO_2 concentrations flatten or decline as a result?

The Hub played an important role in providing real-time analysis on the impact of COVID-19 on fossil fuel CO_2 emissions through published journal papers, the *State of the Climate 2020* report and media activity.

Extensive public-facing communication from the Hub revealed that, contrary to public belief, in 2020, overall levels of CO_2 in the atmosphere continued to grow strongly despite the unprecedented drop in emissions both in Australia and globally. While the 7% annual reduction in fossil fuel CO_2 emissions is significant, human activities still released 34 gigatonnes of CO_2 from fossil fuel emissions in 2020 and consequently there was a continuation of strong growth in atmospheric CO_2.

Findings from the analysis, published through peer-reviewed papers, demonstrated the magnitude of change that will be required to achieve net zero emissions from human activity and stabilise the global climate system. It also emphasised the necessity of deep, significant and permanent changes to global energy, transport and food systems.

■ The Hub played an important role in providing real-time analysis on the impact of COVID-19 on fossil fuel CO_2 emissions.



Blue carbon for climate change mitigation benefits

In much the same way as vegetation on land can absorb CO_2 from the atmosphere and act as a carbon sink to lower atmospheric carbon emissions, Australia's coastal vegetation plays an important role in sequestering CO_2.

Large expanses of mangrove, saltmarsh and seagrass habitats, collectively known as blue carbon ecosystems, are found in diverse coastal and estuarine settings around Australia's coastline. Blue carbon is increasingly recognised for its climate change mitigation potential, and plans are afoot to include it as a method for carbon crediting in emission reduction schemes.

And while mangroves may not inspire as much awe, wonder or beauty as coral reef ecosystems, they play a massive role in coastal environments. Blue carbon ecosystems such as mangroves can accumulate large amounts of carbon (much more than land-based forests – by as much as 40 per cent) and can also store it in their sediments for longer periods than in soil. Moreover, they don't just help mitigate climate change, they also help weather climate change impacts by slowing down waves and protecting our coasts from erosion.

But these blue carbon ecosystems are under threat from climate change, coastal development and coastal squeeze, and ecosystem exploitation. Habitat loss and degradation results in emissions of stored carbon and other greenhouse gases, so a priority for the Hub was to develop strategies to protect these ecosystems against the threats they face.

Coastal management activities need to demonstrate a verifiable increase in ecosystem carbon stocks to be used as a method for carbon crediting in emission reduction schemes. This remains a challenge given there are few studies that directly quantify the carbon stock changes in response to management, and no accepted standard for carbon stock assessment. To address this gap, the NCCC evaluated coastal management strategies that aimed to protect and increase coastal carbon storage, including the use of mangrove planters (pods) to re-establish mangroves in high-energy environments.

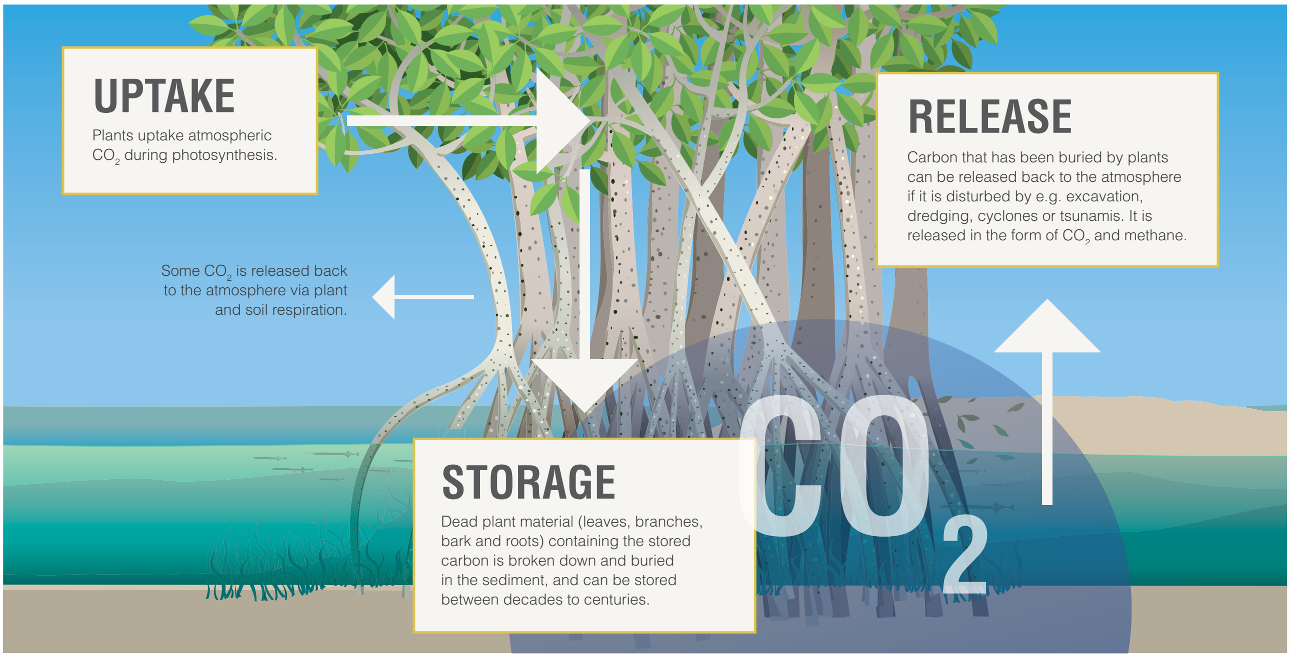
The research showed that restoration approaches can significantly increase blue carbon compared to degraded sites. Recommendations to improve the management of coastal carbon storage include prioritisation of conservation management, extending monitoring timeframes of vegetated coastal ecosystems, more research into greenhouse gas fluxes in open coastal systems, and focusing future research on understudied, high-risk areas.

Hub research also improved accounting methods for blue carbon stocks and the rate at which they accumulate carbon in coastal ecosystems in Australia. This included developing and applying methods to better monitor root distribution and turnover, and developing guidelines for coastal managers to calculate accurate estimates of sediment carbon stock. While blue carbon is not currently included in carbon offset trading schemes, research from the NCCC and the Hub will pave the way for it to be included in such schemes, as well as providing an incentive for protecting and enhancing these important ecosystems.

With increasing awareness of blue carbon's role in climate change mitigation, the Hub's research provides value to governments seeking to develop blue carbon offset methods, and protect and revegetate habitats for carbon sequestration.

Reducing uncertainty around blue carbon in carbon accounting estimates and improving our understanding of the impact of coastal vegetation on the carbon cycle.

Blue carbon for climate change mitigation benefits. Mangroves and other coastal vegetation play an important role in sequestering CO_2 through the process of photosynthesis. While this carbon can be stored and buried. habitat loss and degradation can result in the release of carbon in the form of CO_2 and methane.



Climate model development and applications

Human-induced climate change means that the climate we experienced in the past is no longer a reliable indicator of the climate we will experience in the future. Climate models and projections, including those developed by the Australian research community for ACCESS, are the best-available tools we have to understand and plan for our future climate.

Climate models are continually being improved and updated as science advances and computers become more powerful. Models developed by the Hub in collaboration with our partners are no exception. This ongoing development has enabled Australia to contribute to international assessments of climate change, and equips policy makers and researchers with improved understanding of past and future climate.

Australia's climate model, ACCESS

ACCESS, a collaboration between CSIRO, the BoM, universities and international partners, is the only Australian climate modelling system to have widespread national and international impacts. It provides world-class national weather, climate and Earth system modelling for weather and climate forecasts, and future climate projections.

ACCESS model outputs are also used to generate more refined climate data through 'dynamical downscaling' for the Australasian region, providing climate information at local decision-making scales in the process. These simulations and projections can enable better, more informed policy development and decision-making outcomes.

Outputs from ACCESS have enabled Australia to contribute to international climate assessments, including the IPCC, thereby informing policy-relevant decision-making. The Hub supplied simulations from two distinct ACCESS climate models towards the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Climate simulations submitted to CMIP6, a key input into the IPCC AR6, will provide the latest information on present, and likely future, states of global and regional climate.

The extent of future climate change will depend on human-induced greenhouse gas emissions, and their uptake on land and in the oceans. The ACCESS Earth systems model version 1.5 (ACCESS-ESM1.5) provides Australia with the diagnostic capability to explore these possible future climates and their interactions with the carbon cycle. A later version, ACCESS-CM2, developed through the Hub, incorporates the latest advances in the representation of physical climate processes.

This state-of-the-art model is expected to provide more reliable climate projections in response to future greenhouse gas and aerosol emissions.

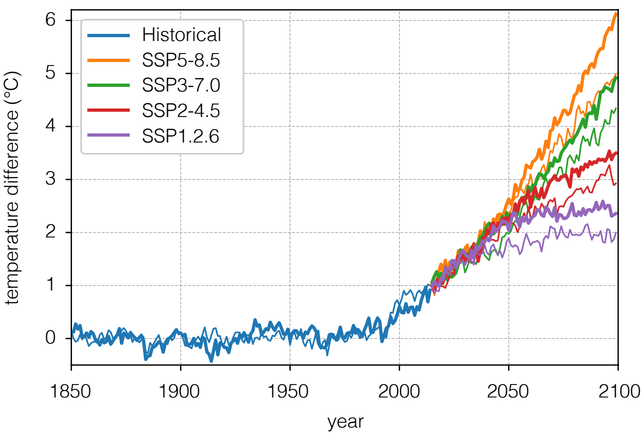
Together, the two ACCESS models deliver a coordinated set of climate model simulations for evaluating global climate models and assessing their climate sensitivity and ability to reproduce the climate of the 20th century. The two versions of ACCESS perform better than most state-of-the-art climate models (submitted to CMIP6) for the simulation of Australia's 20th century climate. Climate simulations projecting decades and centuries into the future are also provided for a plausible range of greenhouse gas emissions and socio-economic pathways.

ACCESS model simulations also enable comparisons between scenarios where atmospheric CO_2 levels stabilise and those where CO_2 levels continue to increase at different rates. This information can be used to investigate how human-induced greenhouse gas emissions affect the climate, especially for our region, and explore the feedbacks between carbon and climate. For example, how terrestrial and ocean carbon sinks respond to climate variability and change, and the influence of this on future climate trajectories.

Outputs from ACCESS simulations provide extensive datasets that encompass a wide range of climate variables such as temperature, rainfall, cloud cover, sea ice extent and ocean circulation. By integrating the latest data, ACCESS model predictions and projections can better inform policy development and decision-making outcomes for the Australian Government and other stakeholders.

Datasets from ACCESS, as well as all other models participating in CMIP6, are freely available through the Earth System Grid Federation.

Helping decision-makers prioritise areas of concern based on the latest scientific evidence.



■ **ACCESS model simulations of both historical and projected global mean surface air temperature.** The simulations are run for a range of possible future emissions scenarios. Temperature differences are relative to the 1850-1900 mean. Thick lines: ACCESS-CM2, thin lines: ACCESS-ESM1.5. SOURCE: CSIRO

Improving Australia's climate model (ACCESS)

Simulations from the ACCESS climate model underpin much of the Hub's science, so continued improvement to achieve better performance is critical for meeting the Hub's goals.

Hub researchers have contributed to continued ACCESS model improvements through science innovations, efficiency, data processing and management techniques, and evaluation of climate model outputs.

Key model improvements to ACCESS-ESM1.5 and ACCESS-CM2 included an upgraded land surface CABLE model and providing a more accurate view of the exchange of carbon, water and heat between the atmosphere and land. Hub research also improved ACCESS simulations of important climate processes in the Australasian region, focusing on rainfall and weather extremes, as well as climate variability and change. This will improve the reliability of multi-year to multi-decadal projections and forecasting on daily to seasonal timescales. These upgrades also bolster the research community's confidence in Australian rainfall simulations in current and future climates.

Ongoing development of ACCESS provides Australia with a national capability to produce climate assessments, and critically assess climate information obtained from the international modelling community.

Improving ACCESS model performance to ensure that Australia's climate modelling capability remains world class.

Decadal forecasting: providing a glimpse into the climate of the future

Understanding what our weather and climate will look like several days ahead is a challenging enough task for meteorologists. But when it comes to forecasts for a year or a decade ahead, things get much more complicated. The ability to make predictions on multi-annual and decadal timescales, known as 'decadal forecasting', is becoming a priority for decision-makers in many Australian industries including agriculture, aquaculture and energy. These industries and many others are vulnerable to climate extremes, such as drought and flooding, which can cause major disruption to their production and profits. They also generally make business planning decisions on 1–10-year timescales.

The Hub kick-started initial work on a decadal climate forecasting capability, with researchers developing conceptual ideas and systems from CSIRO's Decadal Climate Forecasting Project (DCFP) in 2019. Through the DCFP, Australia has made leaps and bounds towards building this capability, with active research still underway.

A decadal climate forecasting capability fills a critical gap in climate information between seasonal (i.e., 3–6-monthly) forecasts currently provided by the Bureau of Meteorology and much longer-term (i.e., multi-decadal) climate projections such as those contributed through Hub research. Developing methods to bridge this gap is regarded by climate researchers around the world as one of the most important scientific challenges.

> **Pushing the boundaries of data assimilation and ensemble forecasting methods to help industry and producers prepare for future climate.**

Co-production of climate knowledge with industry stakeholders

In 2020, CSIRO researchers working on the DCFP collaborated with the Hub and University of Tasmania scientists to advance the utility of multi-year to decadal forecasts. The group, TasLab Engage, engaged with industry representatives from Tasmania to understand user needs for long-term forecast information. Stakeholders covered a broad range of sectors including Antarctic operations, wine production, hydropower generation and emergency services. Through an interview process, the project sought to identify the climate information that would be of most value in their operational planning, risk identification and decision-making.

The TasLab Engage project highlighted the need for co-production of climate knowledge with industry stakeholders as an important step in increasing the uptake of climate information by Australian industry.

■ The Hub collaborated with CSIRO and the University of Tasmania to understand the needs of stakeholders, such as wine producers, for long-term forecast information.

ISTOCK/JANELLELUGGE

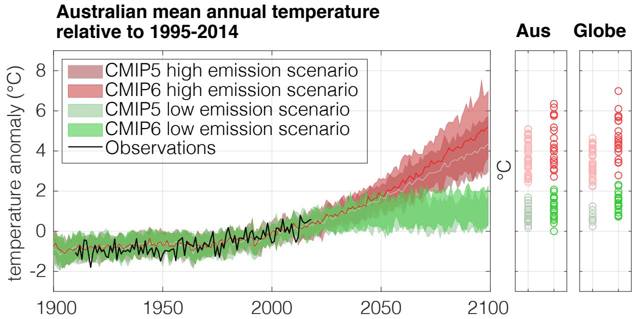
Evaluating the sensitivity of new CMIP6 climate models

To slow the rate of global warming the world needs to reduce greenhouse gas emissions. Currently, countries are working to decrease emissions to meet the Paris Agreement target of maintaining warming 'well below' +2° C.

To reach this goal, the IPCC has identified the need for countries to transition to a low-emissions future, and employ negative emissions technologies to directly pull CO_2 out of the atmosphere.

To determine which targets to implement, and on what timescales, policymakers and scientists rely on accurate estimates of how the climate is likely to respond to a reduction in greenhouse gases. This response is usually expressed in terms of 'climate sensitivity', or the amount of global warming we would experience from increased greenhouse gas concentrations.

Climate models are the primary tool to help decision-makers navigate possible emissions futures using different representative concentration pathways (RCPs). Climate model projections help understand the amount of warming projected to occur, which depends on which depends on the climate sensitivity of the models.



■ **Comparing CMIP6 and CMIP5 climate model simulations of Australian mean annual temperature.** Australian mean annual surface air temperature in observations (ACORN-SATv2), CMIP5 and CMIP6 (relative to 1995–2014) and multi-model mean global warming between 1995–2014 and 2080–2099. CMIP5 and CMIP6 high emission scenarios are RCP8.5 and SSP585 and low emission scenarios are RCP2.6 and SSP126. Circles in the panel to the right show the value for individual models (CMIP5 on the left, CMIP6 on the right). ADAPTED FROM GROSE ET AL. (2020).

With a new suite of climate models released under CMIP6, Hub researchers were able to evaluate the improvement on previous global models. They also investigated how Australia's climate will change into the future using the most current data. Hub analysis of the latest CMIP6 model simulations, from more than 30 different international modelling centres, showed incremental improvements of the model simulations with observations for the last 30 years, compared to the previous Coupled Model Intercomparison Project 5 (CMIP5) models.

Hub researchers were among the first in the world to explore the implications of new CMIP6 models and found some of them had very high climate sensitivity, with some of the models exceeding the previously-accepted range of sensitivity. Some of the CMIP6 models project substantially hotter temperatures by the end of the century than previous models, with some showing warming of up to 7° C for Australia by 2100 if emissions were to continue to rise unabated. These results suggest that the world would need to make greater and more urgent cuts to greenhouse gases to meet the goals of the Paris Agreement. They also highlight the need for research and development into negative emissions technologies to meet this target.

The Hub's evaluation of the CMIP6 models also indicated improved capability in rainfall projections. Although there are still large uncertainties around future changes to rainfall projections over northern Australia in the monsoon season, there is now better understanding of the reasons behind this range. There is now also increased confidence in drying over southern Australia in the cooler months.

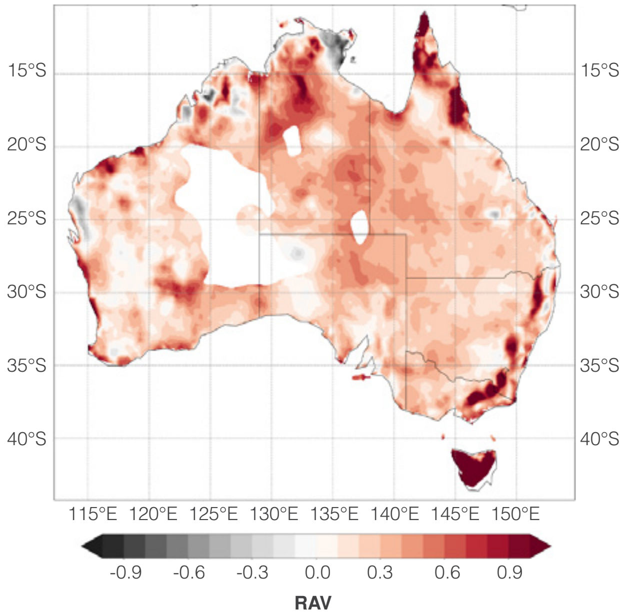
> **Evaluating the latest climate models to ensure the world is on target to stabilise global warming, and to increase confidence in projections.**

Obtaining finer resolution global and regional climate projections

Global climate models, such as those produced for CMIP6, are the primary tool for producing future climate projections. Most models have used spatial resolutions that are too broad (or 'coarse') to capture small-scale climate phenomena or provide climate information at scales useful in decision-making. For example, a typical global climate model represents climate on a spatial scale of about one degree of latitude, or close to 100 km.

Enter regional climate modelling. By using boundary data from global climate model simulations or re-analyses, regional climate models can simulate smaller-scale climate phenomena, such as rainfall, over a limited area (such as 10-20 km scales) and provide higher-resolution regional climate projections that are often better suited for local decision-making purposes. This process is known as dynamical downscaling. The Coordinated Regional Downscaling Experiment (CORDEX) is an international initiative that produces high-resolution regional climate projections. Hub researchers contributed to the first evaluation of the CORDEX-Australasia ensemble to assess its regional climate projections. Findings indicate that CORDEX models are able to simulate Australia's climate reasonably well.

The benefits of downscaled regional climate projections for Australia, compared to global climate models, were also investigated. Researchers from the Hub introduced the concept of 'realised added value' to quantify when and where regional models add value simultaneously in the current climate and project a different climate change signal compared to global climate models. They found that there was realised added value in regional projections for Australia for areas containing geographical features like mountains, lakes and coastlines which affect climate variables like rainfall and sea breezes, respectively. This translated to added value for regions including the Alps, Tasmania and coastlines.



■ **Mean 'realised added value' for a CORDEX-Australasia subset.** Red colours indicate where the downscaling is adding value to the global climate models. SOURCE: DI VIRGILIO ET AL 2020

Regional models also enabled researchers to improve ecological modelling of the Gondwana Rainforests. The Gondwana Rainforests of Australia World Heritage Area exists across several sites, all of which are located on elevated terrain. Improving climate projections in this area is particularly important, given that 40% of the annual water source comes from the interaction of topography with low cloud and fog. Regional climate modelling of cloud height was found to significantly improve the modelling of species distributions in the region. Results will be used to directly inform climate change adaptation plans and other policies for these reserves.

> **Improved confidence in the use of regional climate projections for real-world applications.**

Climate information and services

Producing world-class science and data is one important step along the path towards a more climate resilient Australia but it's certainly not the end of the story. Many stakeholders in Australia need support in accessing, understanding, incorporating and using this science and data in their decision-making.

To help stakeholders consider the implications of climate change, they need climate information and services that make the science accessible through easy-to-understand and use information, guidance and tools.

Working with stakeholders, researchers at the Hub focused on producing climate information and tools that stakeholders could use to assess impact, vulnerability and risk and inform decision-making.

By engaging with stakeholders from the start and adopting co-design principles, Hub researchers successfully demonstrated the utility of Earth systems and climate change information to decision-makers.

Understanding the impacts of climate change on the Northern Territory mango industry

There's no better indicator of the arrival of the Australian summer than the appearance of the familiar golden, greenish hue of mangoes at the local supermarket.

By this point, these sweet and tangy fruits have probably travelled a very long distance to make it there. In fact, there's a good chance they've come from a mango farm on the outskirts of Darwin or Katherine in the Northern Territory. But with temperatures continuing to rise in the Northern Territory under climate change, mango season for some of our favourite varieties could become a less familiar occurrence.

The timing and triggers for important stages of the mango production cycle are likely to be impacted by a changing climate, resulting in lower overall productivity of some varieties of this seasonal crop. This is a concern given that mangoes are the largest horticultural export from the Northern Territory (in 2017–18 it produced almost half of the national mango crop, worth around $90 million).

To improve understanding of the impacts of climate change on Northern Territory mango production, the Hub partnered with the Northern Territory Department of Primary Industry and Resources (DPIR). The aim was to provide the industry with information on current and future risks from climate change to inform adaptation and management options.

Part of the research investigated mango flowering and, specifically, the conditions that initiate it. The Hub looked at three commercial mango varieties: Kensington Pride, Honey Gold and Calypso (as well as three others) to identify the impacts of climate change on suitable conditions for flowering.

Hub scientists used climate projections across three key timescales: the near future (2030), which was relevant for trees already in the ground; the middle of the century, relevant for the next planting; and the end of the century, to inform breeding programs and longer-term adaptation responses.

Under projected warming, results indicate that changes to the maximum and minimum temperatures experienced during the critical months for mango flowering could potentially impact on flowering and fruit production for some varieties of mango.

Findings were summarised in an impact assessment that identified the regions and varieties likely to be most affected by the Northern Territory's increasing temperatures, and also indicated the timeframe in which these changes can be expected to occur.

The project report and a range of associated communication products targeted at specific mango growing regions in the Northern Territory have been made available to growers, and there is considerable interest from the broader horticulture industry across Australia and overseas.

The co-design process employed for this project means that a similar assessment could be rolled out for a variety of other Australian produce. This will enable more climate smart decisions (and more guaranteed delicious Australian horticultural produce) into the future.

> **Helping Northern Territory mango growers identify and prioritise appropriate adaptation options in response to climate change.**

Determining climate change impacts on Victoria's greater gliders

Australia's largest gliding possum, the greater glider, is listed as a vulnerable species due to an 80% decline in populations across southeast Australia over the past 20 years. Native forest logging is recognised as the primary driver for their threatened status, given that gliders reside and forage in tree hollows and canopies.

Unfortunately, climate change is increasing pressure on this already-threatened iconic Australian species. To better inform conservation strategies, Hub researchers teamed up with the NESP Threatened Species Recovery Hub (TSR Hub) to quantify the likely impact of climate change on the greater gliders over the next 50 years. The research focused on ash forests in Victoria's central highlands but also used datasets from the wider greater glider populations of southeastern Australia.

Glider population estimates were generated through a combination of models. This included a forest change model, a habitat suitability model and 'predicted vital rates', which provide data on both fecundity (how many gliders will be produced) and survival (the proportion of gliders expected to remain alive). To enhance data on vital rates, the Hub provided expert guidance on the best use of existing climate change data, adding parameters of temperature, rainfall, humidity, wind and solar radiation, all of which would affect reproduction and survival rates.

The data provided by the Hub enabled TSR Hub ecologists to extend previous analyses and improve the robustness of model predictions about the likely impacts of climate change on greater gliders. As a result, conservation managers are able to make better informed management decisions.

Combining threatened species and climate change data to improve conservation information is just one example of the benefits of a cross-cutting national environmental and climate science program to inform policy options for better management of Australia's climate and ecology.

> **Enabling conservation managers to make better informed decisions on a threatened species through cross-hub collaboration.**

■ Climate change is likely to result in a future decline in conditions suitable for triggering mango flowering in some NT regions.

■ Climate change is increasing pressure on the already-threatened greater glider species.

Case study:

Co-producing climate change projections to inform adaptation planning in the Gondwana Rainforests of Australia World Heritage Area

Towering majestic yellow carabeens, large earthy epiphytes and tiny, darting Hastings River mice are just some of the inhabitants of the World Heritage-listed Gondwana Rainforests of Australia. Stretching from Newcastle to the southeast of Queensland, these rich rainforest communities teem with life. Many of their plant and wildlife species are endemic to Australia, some with ancient origins in Gondwana stretching back millions of years. These forests are also home to over 200 rare or threatened plant and animal species.

Despite their ancient past, the Gondwana Rainforests are vulnerable to climate change. Many plant and animal communities, for example, are now confined near the eastern escarpment and coast where conditions are wetter.

The unprecedented bushfires of Black Summer 2019–20 tore through much of the rainforests and, in the months before the fires, they endured relentless drought, high temperatures and low humidity. Managers at the Gondwana Rainforests WHA have long been concerned about the future of the rainforests under a changing climate. Would they experience drier conditions than they have in the past?

Critically, there was limited analysis of future climate conditions, such as rainfall and cloud cover in the region, to answer the question. This hampered the ability of rainforest managers to plan and respond to current and future climate impacts.

By working directly with Gondwana Rainforests WHA managers, Hub researchers were able to co-design a purpose-built assessment that included the necessary factors for assessing climate change impacts on the rainforests. This approach allowed the Hub to meet the challenge of a lack of data, head-on.

The Gondwana Rainforests are high-elevation forests and receive up to 40 per cent of their annual water requirement from fog. Hill fog (where clouds sit on hilltops) is an important contributor, which means that many animal and plant species are dependent on precipitation direct from clouds rather than rain. The Mountain Frog *Philoria kundagungan* is one example: an endangered species found in the Gondwana Rainforests that lays its eggs in shallow water-filled burrows rather than streams or ponds. Low clouds condensing on the leaves in the forest canopy provide essential moisture to the ground layer of the forest that enables the frog to lay its eggs.

Hub researchers examined the effect of changes in temperature, rainfall and relative humidity on both the high-elevation forests and the key species that live there. Projections were used to analyse the potential climate impacts on Gondwana Rainforests' biodiversity. These pointed to a continued increase in temperatures, but a decrease in humidity, as well as changes to the cloud height. Higher cloud height, especially during the dry season, could lead to a dry climate that is beyond the tolerance of some species, resulting in rainforest community changes. Indeed, even moderate increases in cloud height were found to have significant implications for cloud-water dependent species, especially those located at elevations adjacent to the current cloud base.

Project findings demonstrate that the development and analysis of downscaled climate projections, used in combination with ecological and other data, can support improved risk assessments, climate adaptation planning and management of the Gondwana Rainforests, and other WHAs. This includes assessments for bushfire management, complementing other spatial tools used by land management agencies to assess and mitigate risk.

> **Collaborating with WHA property managers to ensure they are equipped with the most up-to-date and relevant climate advice developed through co-design principles.**

■ The Hub collaborated with World Heritage Area property managers to provide climate projections for the Gondwana Rainforests.

ISTOCK.COM/IAINSTYCH

Updated projections of future water availability and drought

Reduced rainfall reliability under climate change means, for many Australians, the future will be drier. The demand for water will increase but there will be less water available to meet that demand. To respond to this challenge, the water sector, agriculture, industry, communities and environment management sectors must adapt to a changing climate.

To help the water and related sectors prepare, adapt and respond to climate change, Hub researchers updated projections of water resources, drought and hydrological metrics across Australia. Knowledge and datasets from the research have increased the ability of water-dependent industries to access, interpret and incorporate water projections to inform better planning, management and investment decisions.

Water futures

Projections of water futures (water availability and runoff characteristics) have been developed from hydrological modelling informed by the climate change signal in global climate models. Global climate models are already used in the national climate projections produced by CSIRO and the BoM through the Climate Change in Australia (CCIA) website.

The projections show a general drying trend in southern Australia. The projected decline in cool-season rainfall, and the higher potential evaporation, is likely to be amplified as a 20 per cent decline (and possibly up to 40 per cent) in mean annual runoff in south-eastern Australia (under a 2°C global average warming scenario). In southern Australia, the gap between water supply and water demand will increase unless our use of water changes. Rainfall and runoff changes in northern Australia are less certain.

Australia-wide, climate variability will remain high in the future, with wet years and dry years, but against a background drying trend in southern Australia.

New hydroclimate and drought projections to inform future planning, management and investment for the future availability of water.

Drought

Hub researchers developed a new set of hydrological drought projections for Australia that included the multiple factors impacting drought conditions such as rainfall, temperature and evapotranspiration. The projections encompass percentage time spent in drought, mean drought duration, drought frequency, and how drought intensity may change under a warmer climate. By broadening the indices beyond the single rainfall-based drought index and incorporating a soil moisture-based index, the projections provide more information on drought in Australia than ever before.

Results indicate that Australia will spend more time in drought, with longer and more intense drought conditions, particularly across southern and eastern Australia.

■ Hub researchers developed a new set of hydrological drought projections for Australia.

ISTOCK.COM/MIKULAS1

Case study:

Building understanding of climate change in the Northern Territory

Climate change is posing a challenge for all Australians. In the Northern Territory the community is exposed to extreme events including cyclones, storm surges and flooding. Additionally, many communities are remote and vulnerable to climate change impacts. They also face the inherent tyranny of distance, which increases costs and leads to supply chain issues.

The Northern Territory Government has formally recognised climate change as a challenge and, in 2020, publicly committed to taking action to maximise the wellbeing of Territorians. This means ensuring Territorians understand the risks posed by a changing climate; how they can act to reduce greenhouse gas emissions to limit further climate change; and how to manage the change that is now unavoidable.

The Hub was commissioned to provide advice and recommendations on a climate-smart future, to help the Northern Territory Government develop relevant climate strategies and actions.

The resulting report, *Climate Change in the Northern Territory – State of the science and climate change impacts* provides a plain-English summary on the current scientific evidence for global climate change, the observed changes in the Northern Territory, future climate projections for climate extremes such as drought and fire weather, and a detailed list of expected impacts on the community including health, marine resources, infrastructure, energy, ecology and water supply. As a public-facing resource, it draws heavily on peer-reviewed and high-quality scientific data, including the *State of the Climate* report series and Hub research, to convey the latest science on climate change.

The report will be used to inform policy and assist decision-makers to build a climate-smart future, and serve as a first stop for Territorians who want to understand how climate change will affect them.

Helping the Northern Territory to build a climate-smart future and sustainable communities.

Meeting user needs for sea-level rise information

The rate at which global mean sea-levels are rising is steadily increasing. By 2100, sea-levels around Australia are expected to rise between 45 and 82 cm, depending on the future global greenhouse gas emissions trajectory and the fate of large ice sheets. While some degree of rise is locked-in by the end of the century, the rate of expected sea-level rise is not projected to be uniform. Sea-level rise varies substantially at different locations around Australia and is likely to continue to do so in future.

Cold and warm ocean currents play a big role in modulating the rate of rise, as do the Antarctic and Greenland ice sheets. Adding to that, atmospheric processes and large-scale climate drivers, including the ENSO, cause annual fluctuations in different regions.

Information on future sea-level rise is needed for a range of coastal adaptation and management decisions. These include how much sand to apply for counteracting beach erosion, designing the height and strength of coastal protection and planning for future developments in the coastal zone. But different kinds of decisions require different kinds of information.

To understand what information is required, the Hub undertook an analysis of the needs of decision-makers and the types of sea-level rise information that were most relevant to their needs. The research highlighted the importance of co-designing sea-level information with producers and users.

The Hub also provided the National Climate Change Adaptation Research Facility (NCCARF) with the latest projections of sea-level rise for the 225 coastal councils in Australia. Projections were provided for each decade from 2020 to 2100, under four emissions scenarios. Information on user-needs was communicated through guidance material and extensive stakeholder workshops. The project ensured current knowledge was delivered to the community, particularly coastal planners and managers, in a coherent and efficient way that would aid in decision-making and planning for future coastal change. The project used the latest regional climate projections for Australia and, working with NCCARF, included these projections in 'CoastAdapt', a tool that is used extensively by coastal councils and other coastal planners, managers and relevant governments. This has greatly increased the uptake of Hub research across councils and communities.

Providing updated projections of sea-level rise to those who need it most.

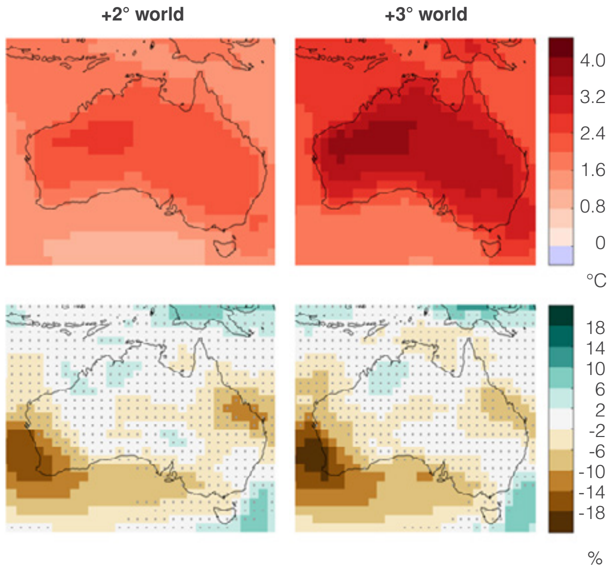
Reframing climate projections for global warming targets

Climate projections can help users navigate different climate futures under a range of equally plausible emissions scenarios. The standard used by the international climate community is Representative Concentration Pathways (RCPs). These emissions scenarios have been adopted by the IPCC in their widely-publicised reports, which are targeted at policy makers and researchers, as well as the wider community.

RCPs allow analysis, through climate models, of what changes in climate might look like at various future times, depending on the extent to which greenhouse gas emissions are mitigated (e.g., low- or high-emissions scenarios).

Since countries signed up to meet the targets of the international Paris Agreement in 2015 (+1.5° C or at least 'well below' +2.0° C above pre-industrial levels) there have been more users of climate change information than ever before. Many users also have more sophisticated needs for future climate risk information, including primary producers, local and state governments and the wider community. With new users comes a new need to understand regional climate change impacts and their implications under the international Paris Agreement targets, as well as at other possible levels of warming (+3 ° C). This is because many of the impacts of climate change scale with warming.

To meet this need, Hub researchers produced new climate change projections to describe Australia's future climate under a range of global warming scenarios including +1.5°, +2° and +3° C. Rather than just emissions scenarios, this allows users to visualise and compare local climate change impacts under different degrees of global warming.



Projected change in Australian average annual temperature (top) and rainfall (bottom) at 2°C and 3°C global warming levels, based on CMIP5 models. Top: Temperature change is presented as °C change relative to the period between 1850–1900. Bottom: Rainfall change is shown as the percentage change relative to the period between 1986–2005. Dots show where the model agreement is less than 80%.

This provides decision-makers with relevant information on what the Paris Agreement targets may mean for their local climate. The new projections are now available on CCIA, Australia's national climate change projections website. The new web content provides information and guidance on the broader context around global warming level projections, including where the world is at, when each level could be reached, how much each state and territory has warmed since the 1850–1900 baseline, and much more.

> **Producing a new set of climate projections to help users navigate a +1.5°, +2° or +3 °C world.**

Making regional climate change projections information more accessible

What will Australia's climate look like in 2050? Regional climate projections show that even if we significantly reduce global emissions, Melbourne's climate could look closer to Adelaide's, and Adelaide's climate could be more like that of Griffith in New South Wales. Ongoing global emissions will result in even greater changes.

These are examples of the data and climate information captured by Australia's national climate change projections website, Climate Change in Australia (CCIA). The platform is based on regional national climate change projections developed by CSIRO and the BoM in 2015/16, and uses models from CMIP5.

Over the past five years, CCIA has provided a valuable national resource that underpins understanding about climate change, what various regional and city climates will look like by 2030, 2050 and 2090, and what these changes will look like under different emissions scenarios (low, medium or high).

The needs of CCIA users have progressed significantly since the website was initially designed. Likewise, the user base has broadened from researchers and other technical users to the private sector and non-research users, such as local governments and coastal managers.

With this in mind, Hub researchers set about improving the functionality and navigation of the CCIA website, making it easier to find and use the climate change projections information, data and tools that stakeholders need.

As well as improvements to CCIA navigation and accessibility functions, new content was added, including Australian climate change projections based on global warming levels since the pre-industrial era. High-level climate statements on past and future changes for all states and territories, and at a national level, have also been added to the CCIA website.

> **Helping to improve Australia's national resource on future climate change and empower users to access climate change information.**

The cost–benefit of climate change science and services: what's it worth?

There's no disputing that climate change science is valuable to society and Australia's economy. Much of climate science, however, is considered 'public good', which makes it difficult to quantitatively estimate its economic value.

Climate science projects delivered by the Hub often fall into this public good category and provide inputs into the broader climate change services value chain. This chain typically involves many stages of knowledge creation, decision-making and stakeholder engagement, with each stage adding value as evidence to underpin policy development and/or planning processes.

To better understand the value proposition for climate change science, it helps to ask, what would the economic impact be of not investing in climate change science? The Hub set out to answer this question by developing a conceptual cost–benefit framework to demonstrate the impact and benefit of public good investment in climate change science. Researchers compared early and late investment in science-based services under contrasting (high and low) emissions scenarios to analyse and assess impacts on GDP growth.

The Hub's analysis suggests that government investment is enhanced regardless of whether it is made under a high- or low-emissions scenario. The greatest gain, however, was made from early investment under a high-emissions scenario (as compared with the same investment strategy under a low-emissions scenario). The early-high investment scenario results in just over $67 billion per year of benefits to the economy in 2100, after all costs and other factors are considered. This is likely because early investment in climate services under a high-emissions scenario would help mitigate the economic damage of climate change, particularly given that future changes in climate are greatest in a high-emissions world. By comparison, the late-low investment scenario is the poorest outcome, providing benefits to the economy of $44 billion per year in 2100.

The Hub's analysis indicates that, when applied effectively, climate services have the potential to enhance the productivity, efficiency, value and resilience of the Australian economy across multiple sectors.

> **Developing a conceptual cost–benefit framework to measure the economic value of the Hub's research outputs to the Australian economy and wider society.**

■ Crossing the floodwater, Sunshine Coast, Queensland, Australia. ISTOCK.COM/ISTIMAGES

■ Scientists returning from a wetland with samples collected to assess the health and carbon sequestration capacity of the ecosystem, Victoria. ISTOCK.COM/TENEDO

Building climate capability

Over the lifetime of the Hub there has been a key shift in the demographic seeking climate information and services. Specifically, it has expanded to include a wider variety of policy and decision-makers, with a shift towards the business and finance sectors. There is also a growing number of stakeholders seeking to understand the climate risks posed to primary production, industry and ecosystem management.

Recognising the value of the Hub's extensive climate change information and services, we worked with stakeholders, including from the financial services sector, to upskill their climate literacy and understanding of climate science. We found that building the climate science capability of our stakeholders enabled them to more confidently access, use and incorporate our science into their work. To strengthen our science-policy interface, we also focused on upskilling our researchers to better understand and communicate with Australian policy and decision-makers.

Helping stakeholders to navigate climate change science

With more science-based climate change information available than ever before, there is still a lot of stakeholder uncertainty about how the climate system works, how the climate is changing, and what climate projections tell us. There is also limited understanding about how to find and use this information to inform policy and decision-making.

To fill this gap, the Hub developed and ran a series of climate change literacy workshops. These workshops provided participants with an introduction to understanding the climate system, climate change science, and climate change modelling and projections. The workshops were designed to provide advice on choosing the most appropriate climate change information, and navigating a Hub-developed step-by-step process to use climate change information for a better understanding of climate change impacts.

The workshop was trialled over two years and the range of stakeholders included WHA managers from Shark Bay and Gondwana Rainforests, Northern Territory mango growers, the Victorian Government and energy and water managers from Western Australia. Feedback from workshop participants has been used to adapt and refine the toolkit to a simple five-step health check for quickly identifying climate change impacts.

In addition to developing basic climate literacy, the workshop series can be used for climate impact assessments that provide stakeholders with a better understanding of their current and future climate risks. The end result is decision-makers who better understand the climate system and climate projections, and have the confidence to find and use climate change information to inform decisions that will affect the management of Australia's environment, economy and communities into the future.

Empowering Hub stakeholders with the confidence to find and use climate change information, and increasing uptake of climate science information across sectors.

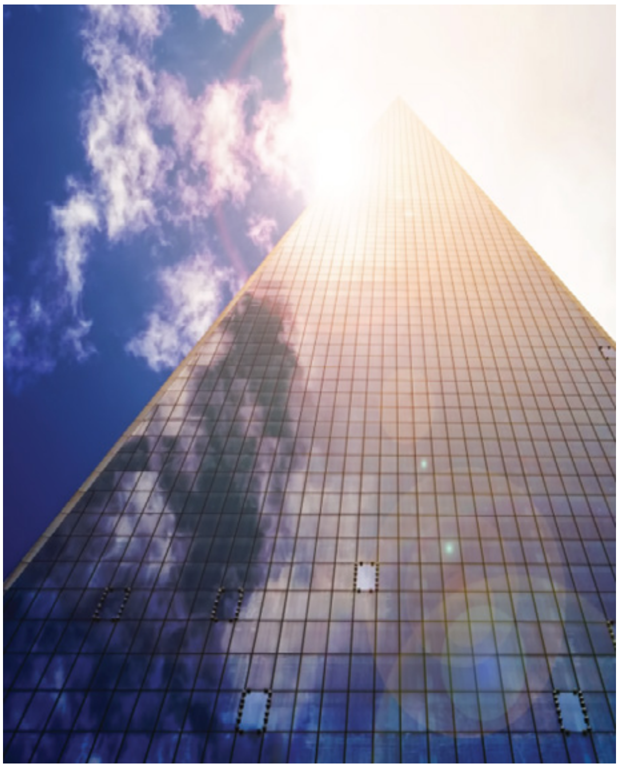
'The workshop demystified a lot of things and I feel more confident when talking about projections.'

– Participant, DELWP Melbourne workshop, December 2019.

'The best thing about the workshop was making sense of the information available and how this can practically be applied in our decision-making.'

– Participant, DELWP Melbourne workshop, December 2019.

■ The Hub helped guide robust, peer-reviewed, and science-based evidence to inform the Australian industry-led CMSI initiative.



Case study:

Integrating the science and business of climate change

Climate change presents significant challenges to the financial services sector, including to risk management and financial disclosures. Until recently, there were no agreed scientific standards in place for Australian industry to measure and report on climate change risk.

The Climate Measurement Standards Initiative (CMSI) is an Australian industry-led collaboration designed to assist with, and support climate-related financial disclosures. It represents a first step towards ensuring Australia has a scientifically-rigorous approach to standardised scenario analysis for understanding risk and framing financial disclosures in relation to climate change. This standardised approach was developed in response to the recommendations from the Task Force on Climate-Related Financial Disclosures.

Using a co-design approach, the CMSI brought together insurers, banks, scientists, reporting standards professionals and consultancy service providers to develop open-source technical, business and scientific guidance for projections-based physical climate risk assessment of the future repair and replacement costs of Australian buildings and other infrastructure assets. The Hub played an instrumental role in this initiative, guiding the input and expertise of Australian climate scientists across the Hub's partners to frame and facilitate application of robust, peer-reviewed, science-based evidence to inform industry risk and associated decision-making.

The CMSI has provided better risk information through a standardised approach. This allows for more consistent and rigorous reporting and, therefore, better decisions for investors. The CMSI initiative is part of a global endeavour to better integrate the science and business of climate change.

'At the start of the Hub, the challenge was to put climate intelligence in the hands of the people who needed to use it, including the financial services sector, and we did it.'

– Nick Wood, Climate Policy Research and Inaugural Chair, Hub Stakeholder Advisory Group.

Providing robust climate science to underpin informed decision-making around risk.

Supporting early career researchers

The Hub has been committed to providing access to unique academic and professional development opportunities for early career researchers (including PhD students) associated with the Hub via its extensive stakeholder network.

The Hub's 'Young Professional' events brought together early career researchers from partner agencies with young industry professionals from the banking, finance, insurance, actuary, engineering and government sectors to consider climate risks under hypothetical scenarios. They were invited to collaborate, and use expertise and data across the various sectors, to raise awareness of the availability and potential applications of climate change science, and to develop innovative solutions.

> 'I still think climate change is very complex. However, it no longer feels like it is a problem I can't tackle – we can make relevant input into how communities deal with climate change.'
>
> **– Lisa Ye, a decision-maker who attended the 2018 Young Professionals event.**

As well as participating in these events, Hub early career researchers were provided with various opportunities to present science to policy colleagues in state and federal government agencies. The Hub also facilitated engagement between early career researchers and First Nations peoples to better understand climate change impacts on their communities. Early career researchers were also encouraged build their science communication skills at workshops, through webinars and by developing easy-to-read communication products on the Hub's research.

These activities all aimed to increase the ability of early career researchers to understand and communicate with key stakeholders across government, industry, the finance sector and the public. These are skills that will stand them in good stead, and help to ensure Australia's next generation of senior climate researchers are equipped with the skills necessary to articulate the importance of their research in informing decisions which affect the future of Australia.

Investing in the next generation of climate scientists to cultivate a world-class climate science capability.

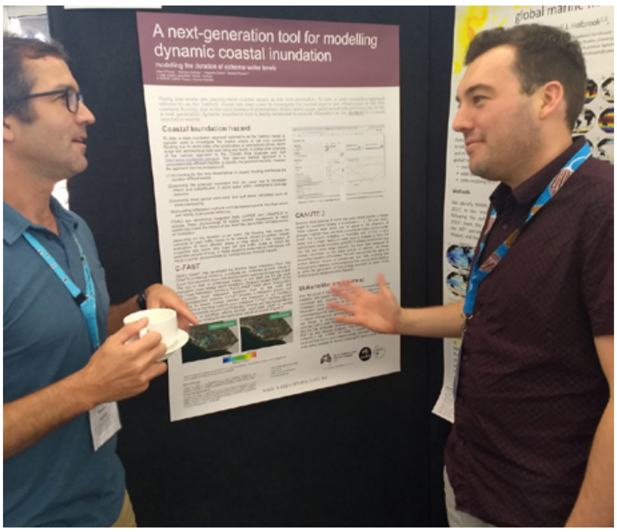
Informing the strategic development of climate services in Australia

In the context of ongoing climate variability, extremes and change, there has been an increasing demand in Australia from stakeholders for access to relevant, usable and scientifically robust climate information services.

Australia has an existing climate services capability for end-users, including tools, websites and platforms, guidance, data and technical expertise. This capability includes the Bureau of Meteorology's website; modelling platforms such as ACCESS with digital platforms such as CoastAdapt; CCIA; and various state-based climate portals. This capability helps users generate and access climate intelligence and in part, turn climate information into 'actionable knowledge'. Some of these platforms specifically help users assess and manage risk, and can be used to help inform the development of adaptation strategies. Unfortunately, most of these climate services are not well coordinated and operate across multiple timescales, from weather to climate change. They are also hosted and maintained by different agencies, somewhat independently of one another. A future focus of climate science and services in Australia will be to improve the connection and consistency between these largely government-funded services.

> 'The Hub has made a profound contribution to climate science. In doing so, it has built understanding and acceptance of the science, resulting in millions more Australian – not just researchers – being able to access knowledge and prepare for climate change.'
>
> **– Juliet Bell, CSIRO Climate Resilient Enterprise Initiative.**

■ Early career researchers were supported through the Hub to build their science communication skills with stakeholders across government, industry, the finance sector and the public.



A national climate service

The Hub was commissioned by the Department of Agriculture, Water and the Environment (DAWE) to advise on a national climate services capability for Australia. This culminated in a report to the National Climate Science Advisory Committee entitled *Informing strategic development of a national climate services capability for Australia.*

The report documented the need for, and an approach to, development and delivery of a comprehensive and nationally-coordinated climate services capability for Australia. The report was based on extensive stakeholder consultation, a comprehensive literature review, and research into existing capabilities, market capability, and needs, risks, challenges and options for achieving this vision.

What does the vision for a national climate services capability for Australia look like? It would span the public and private sectors, and take the form of an integrated platform for developing and delivering climate intelligence at scale. It would be a key feature of a sovereign risk capability for building climate resilience across Australia's economy and communities. Its core offering would include federated, web-based digital climate intelligence platforms for the delivery of end-to-end data and information services that address both physical and transitional risk. And it would connect national and state-based data, information, analytics and guidance.

A national climate services capability would also strengthen relationships between users and providers of climate information. This could be achieved by linking core products and services (typically open-source or public good), such as climate observations, model-based projections and related assessments, with differentiated products and services (typically proprietary protected/user pays), such as more bespoke decision-support tools and climate risk assessments tailored for specific businesses, industries and sectors.

As the report outlines, it would also be necessary to complement the digital delivery of services with appropriate user support including a help desk service, capacity development in the form of training courses, and outreach support in the form of targeted communication and knowledge brokering.

The report provides an important foundation for design and implementation of new national initiatives including the DAWE-funded Australian Climate Service and Climate Services for Agriculture initiatives, the NESP Climate Systems Hub and the CSIRO Climate Resilient Enterprise Initiative.

Next generation climate change projections

Over the past decade the scientific community has significantly improved its understanding of Australia's climate processes, some of its key drivers, and how these may change as the world continues to warm. During this time, the communication of regional climate projections, including those made available through the CCIA website, has also contributed to a shift in public and stakeholder awareness of climate change. The projections, released in 2015/16, remain world class.

In 2021, Australia and the world are at a turning point in the management of climate risks and opportunities. Changing user needs and advances in our understanding and modelling capability mean that new projections are necessary to ensure that Australian stakeholders have access to products based on the very latest science. This includes new model data, information and developments coming from international activities, including the IPCC AR6, and the new generation of regional modelling developed under the CORDEX.

The Australian scientific community is well-placed to deliver the next generation of climate change projections. Working with its key partners, the Hub developed a plan for a program of next-generation climate projections for Australia. They determined that the aim of the program was to set out the need for, and an approach to, the next generation of climate projections for Australia.

Ideally, it should be an approach that strengthens support for our domestic capabilities and effort, as well as leverages international efforts to produce new regional projections. These recommendations were summarised in a report at the request of the National Climate Science Advisory Committee.

The Hub recommended a staged approach, spanning upwards of four years, to deliver and communicate updated projections, and also plan further enhancements and improvements. Some of the key recommendations were to elevate a co-design approach across agencies and stakeholder groups in order to meet user needs, and to update projections based on simulations from CMIP6 and future scenarios from the Shared Socio-economic Pathways being used in the IPCC AR6. This extensive consultation and engagement activity will provide a solid foundation for the activities of the new NESP Climate Systems Hub and the Australian Climate Service.

> **Informing the next generation of regional climate information to ensure it maintains relevance, usability and scientific credibility.**

Looking ahead

Over the last six years, the Hub produced much new science recognised both nationally and internationally which has led to improved confidence in the use of climate change information.

The Hub made climate science more readily accessible and changed how climate science is viewed in Australia, particularly by industry. It has helped create more resilient communities and ecosystems, with a better understanding of climate variability and the impacts of climate change. Its outputs are already informing policy, decision-making and environmental management.

Much of the Hub's impact is owed to the underpinning science, co-design process and knowledge brokering activities that helped identify user needs, and ensured that the science was answering the right questions.

The Hub's investment and delivery in critical domain areas such as climate services and has also resulted in tangible on-ground outcomes, including the establishment of a sovereign climate risk capability for Australia going forward.

Under the next phase of the Australian Government's National Environmental Science Program (2021-2027), the Climate Systems Hub will continue to build on the research and outcomes produced under the ESCC Hub. The Climate Systems Hub, as well as other new initiatives and programs in the climate science space, are poised to capitalise on the momentum of the growing need for climate services, and a growing stakeholder base in this area.

■ Back cover: Scientist measuring greenhouse gas emissions at a wetland using a portable gas analyser to understand the role of tidal marshs in carbon sequestration. ISTOCK.COM/TENEDO

ISTOCK.COM/THURTELL

Earth Systems and Climate Change Hub

National Environmental Science Programme

The Earth Systems and Climate Change Hub is funded by the Australian Government's National Environmental Science Program.

www.nespclimate.com.au