Earth Systems and Climate Change Hub

National Environmental Science Programme

Ocean knowledge supporting climate decisions

June 2021

Earth Systems and Climate Change Hub Report No. 27

Australian Government

National Environmental Science Programme

The Earth Systems and Climate Change Hub is supported by funding through the Australian Government's National Environmental Science Program. The Hub is hosted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and is a partnership between CSIRO, Bureau of Meteorology, Australian National University, Monash University, University of Melbourne, University of New South Wales and University of Tasmania. The role of the Hub is to ensure that Australia's policies and management decisions are effectively informed by Earth systems and climate change science, now and into the future. For more information visit www.nespclimate.com.au.

Citation

NESP Earth Systems and Climate Change (ESCC) Hub. 2021 *Ocean knowledge supporting climate decisions*. ESCC Hub Report No. 27. Earth Systems and Climate Change Hub, Australia.

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Published June 2021

This report is available for download from the Earth Systems and Climate Change Hub website at www.nespclimate.com.au.

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Executive summary

Climate variability and change have resulted in economic and societal challenges. The ocean is an integral part of the Earth's climate system through its ability to store and globally redistribute large amounts of heat, freshwater and carbon. The oceans surrounding our island nation – the Southern, Pacific and Indian Oceans – dominate the oceans response to heat and carbon uptake and circulation changes that impact sea-level rise, and climate extremes. Understanding of ocean circulation and key ocean processes are vital for ocean forecasts. That understanding is crucial to project ocean and terrestrial climate conditions in future climates under a range of scenarios, assess the impacts of climate change and develop mitigation and adaptation strategies.

This report summarises ocean research conducted by the Earth Systems and Climate Change Hub of the Australian Government's National Environmental Science Program. This research has provided new insights into the role of the ocean in the climate system. These ocean observations, modelling and assessment studies have laid the foundation for more reliable predictions and projections of severe climate events, global and regional sea level rise and development of future climate scenarios.

Ocean climate research depends on sustained ocean observations and ocean models. The Earth Systems and Climate Change (ESCC) Hub supported the analysis of ocean observations (rather than their collection) as well as the involvement of researchers in national and international science reviews and program developments. Researchers under the Earth Systems and Climate Change (ESCC) Hub have provided leadership in the international Global Ocean Observing System, as well as in national ocean observation initiatives, to develop a fit-for-purpose, sustained and prioritised ocean observing system. These critical ocean observation and ocean model developments support ocean detection and process studies that lead to more reliable weather forecasting and climate projections models. In these leadership roles hub researchers have been very effective in leveraging international and national investment in ocean observations of the Indian, Pacific and Southern Oceans. ESCC Hub researchers involved in these international activities ensure that Australia's interests and Australian-based climate change information is appropriately recognised and included in global assessments.

ESCC Hub research has focussed on the regional oceans that play a critical role in Australia's climate and its variability, namely the Southern, Indian and Pacific Oceans. This research has quantified that the ocean has taken up over 90% of the additional heat added to the Earth's system due to human activities. Importantly, Hub research has highlighted that the Southern Hemisphere oceans accounted for 67–98% of the total global ocean heat increase. ESCC Hub researchers, using ocean model experiments, have shown that the simulated Southern Ocean heat uptake is sensitive to the vertical resolution at the surface. These findings offer guidance for examining Southern Ocean heat uptake and storage in future modelling studies and observations.

Ocean warming coupled with changes to the wind field that drive the ocean, result in changes in the ocean circulation and its influence on land-based processes. For example, ESCC Hub researchers have found that ocean warming and circulation variability at the Antarctic continental margins has resulted in accelerated melting of the ice shelf from below, with implications for sea-level rise and the deep ocean circulations. Hub research has focused on the East Australian Current where change in the current's dynamics have influenced the ocean properties along the east coast and in the Tasman Sea. Similarly, heat transport in the Indian Ocean currents is influenced by eddies and waves propagating from the coast of Western Australia.

The climate system knows no boarders, and while Australia's climate science efforts are world-class, the size of our capability is relatively small. Global research initiatives and processes such as the Intergovernmental Panel on Climate Change (IPCC) can provide Australia with access to many times our contribution of data, information, knowledge and expertise – all of which contributes to and informs our own understanding of Australia's climate and how it may change under a warming climate.

There remain knowledge gaps in our understanding of how the ocean influences Earth's weather and climate across the full spectrum from daily to interannual and multidecadal time scales. Continued targeted research into key ocean knowledge gaps will lead to more stronger decision-making processes required to plan and implement policies to the benefit of all society.

This research may assist in answer climate-related questions such as 'what do changes in East Australian Current (EAC) variability mean for regional fish recruitment and stocks, and how this knowledge can be used to make management decisions accordingly?'. Or, 'how does ocean heat uptake and regional ocean circulation influence rising sea level on heavily populated coastal areas to make them less or more vulnerable to the impacts of tropical and extra-tropical cyclones?'. In this way, increasing our ocean knowledge will continue to support climate decisions.

ESCC Hub researcher Dr Bernadette Sloyan inspects the ocean while aboard the RV *Investigator* on its 2019 East Australian Currant voyage. Image credit: Thomas Moore, CSIRO

1 Introduction

The ocean is vast. Covering more than 70% of the Earth's surface, it contains more than 97% of the Earth's water and is the primary source of moisture for Earth's hydrological cycle. The ocean is a key component of the climate system; absorbing heat, nutrients and carbon dioxide, yet it is often said that we know less about the ocean than we do about the moon.

The spatial distribution of ocean regions and continents is uneven across the Earth's surface. In the Southern Hemisphere, the ratio of ocean to land is about 4 to 1, much larger than the Northern Hemisphere's 1.5 to 1 ratio. The greater abundance of ocean surface in the Southern Hemisphere has some significant effects on Australia's environment at local, regional and larger scales. The ocean's influence on our climate reaches from the coast to far inland and affects us at timescales of weeks to centuries. For example, Australian rainfall is strongly influenced by the El Nino-Southern Oscillation, arising from equatorial Pacific ocean-atmosphere interactions. Study of the Earth's climate system must therefore include the investigation of the ocean and sea-ice physical and biogeochemical processes, including interactions with the atmosphere, ice, land and biosphere.

Climate change is already significantly affecting our oceans, with more change projected into the future. Associated loss of sea ice due to warming oceans is impacting global ocean circulation. Higher sea surface temperature is increasing the potential for extreme weather and sea level rise heightens the dangers of coastal flooding. It is therefore vital to fill key knowledge gaps in our understanding of the ocean. This will support climate assessments that meet the growing demand for reliable information to inform mitigation and adaptation policies, weather and ocean services, multi-hazard early warning systems and climate and ocean health applications.

To manage and mitigate human impacts on our environment, understand weather patterns and make climate and weather predictions, it is important to understand the key dynamical processes that set the ocean circulation and ocean-atmosphere interactions. Research into our changing oceans under the Australian Government's National Environmental Science Program Earth Systems and Climate Change Hub has contributed to improved knowledge of ocean processes, ocean circulation and ocean modelling, and has led to the provision of climate information required for assessment of climate risk and development of mitigation and adaptation policies.

This report outlines the global and national impacts of research conducted under the Earth Systems and Climate Change (ESCC) Hub, in collaboration with national and global partners (Section 2), the ocean's influence on Australia's climate variability (Section 3), the causes of this variability (Section 4), how the ocean is driving Australian climate impacts (Section 5) and concluding remarks (Section 6). The report describes research conducted by the ESCC Hub as well as research conducted by the broader research community.

2 Impact of the ocean research conducted under the Earth Systems and Climate Change Hub

The oceans surrounding Australia are part of the ocean global commons. Australia is in a unique geographical position with respect to the global ocean circulation. To the south, the Southern Ocean is the only circumpolar ocean; it plays an important role in the global circulation, enabling inter-basin exchange as the conduit for Atlantic, Indian, and Pacific Ocean water masses to freely exchange and interact. At our northern boundary, the Indonesian Throughflow (ITF) carries Pacific Ocean warm pool waters through the Indonesian Seas and into the Indian Ocean, providing the only tropical pathway for exchange between basins in the global circulation. Along our western and eastern coastlines, the Leeuwin Current and East Australian Current sweep warm, tropical waters southward.

Ocean observations of the Southern Hemisphere oceans have contributed immeasurably to our knowledge of the ocean and our ability to respond usefully to calls for information regarding the important climate needs. ESCC Hub researchers have taken on major international and national leadership roles in advocating for and developing monitoring programs within the framework of the Global Ocean Observing System (GOOS) and associated networks and the Integrated Marine Observing System (IMOS). In these leadership roles we have been very effective in leveraging international and national investment in ocean observations of the Indian, Pacific and Southern Oceans close to our shores.

Ocean research undertaken by the Earth Systems and Climate Change Hub has articulated the strong influence of the ocean on the global and Australian climate. It has provided highly valuable scientific insight and significant input to international and national climate and ocean assessment reports, such as the IPCC Assessment Reports and Special Report on Oceans and Cryosphere in a Changing Climate, Bulletin of the American Meteorological Society Annual State of the Climate reports, CSIRO/Bureau of Meteorology State of the Climate reports and State of the Environment reports.

Contribution to the IPCC process, and to its assessment reports including the Special Reports and upcoming IPCC Sixth Assessment Report (AR6), is of global importance. The IPCC is one of the most trusted sources of climate science information and is recognised and used by government's around the world. These reports provide evidence which can underpin their policies and management decisions. The IPCC is embedded into the science-policy interface through its formal inclusion in the United Nations Environment Plan (UNEP) and the World Meteorological Organisation's World Climate Research Program (WCRP) and in each country, including Australia, through their focal point.

Not only have ESCC Hub researchers contributed to the IPCC process, but the IPCC reports themselves contribute to an important aim of the ESCC Hub - to provide the best available science to ensure Australia's policies and management decisions are effectively informed by Earth systems and climate change science, now and into the future. This in itself highlights the importance of Australia's contributions to the IPCC and other global research programs and initiatives. This in itself highlights the importance of Australia's contributions to the IPCC and other global research programs and initiatives.

The climate system knows no boarders, and while Australia's climate science efforts are world-class, the size of our capability is relatively small. Global research initiatives and processes such as the IPCC can provide Australia with access to many times our contribution of data, information, knowledge and expertise – all of which contributes to and informs our own understanding of Australia's climate, and how it may change under a warming climate.

The leadership and participation of ESCC Hub researchers in international and national ocean reports and initiatives, ocean observing systems and model development also adds to the Hub's reputation as a trusted provider of climate science information for Australian policy makers and industry. It highlights the importance of the research undertaken by the ESCC Hub and our world-class status of providing the best available information to undertake assessments and provide projections of climate change. Finally, ESCC Hub researchers involved in these international activities ensure that Australia's interests and Australian-based climate change information is appropriately recognised and included in global assessments. These observations, models and assessment studies have laid the foundation for more reliable predictions and projections of severe climate events, global and regional sea level rise and development of future climate scenarios.

3 The oceans' influence on Australian climate variability

Australia's large agricultural sector results in Australia having a highly climate sensitive economy. For example, many areas of the economy are adversely impacted by climate variability with a $10 billion (1.6%) decrease in GDP associated with droughts. In regional Australia, the impact is much larger at 10% of GDP (Adams et al, 2002).

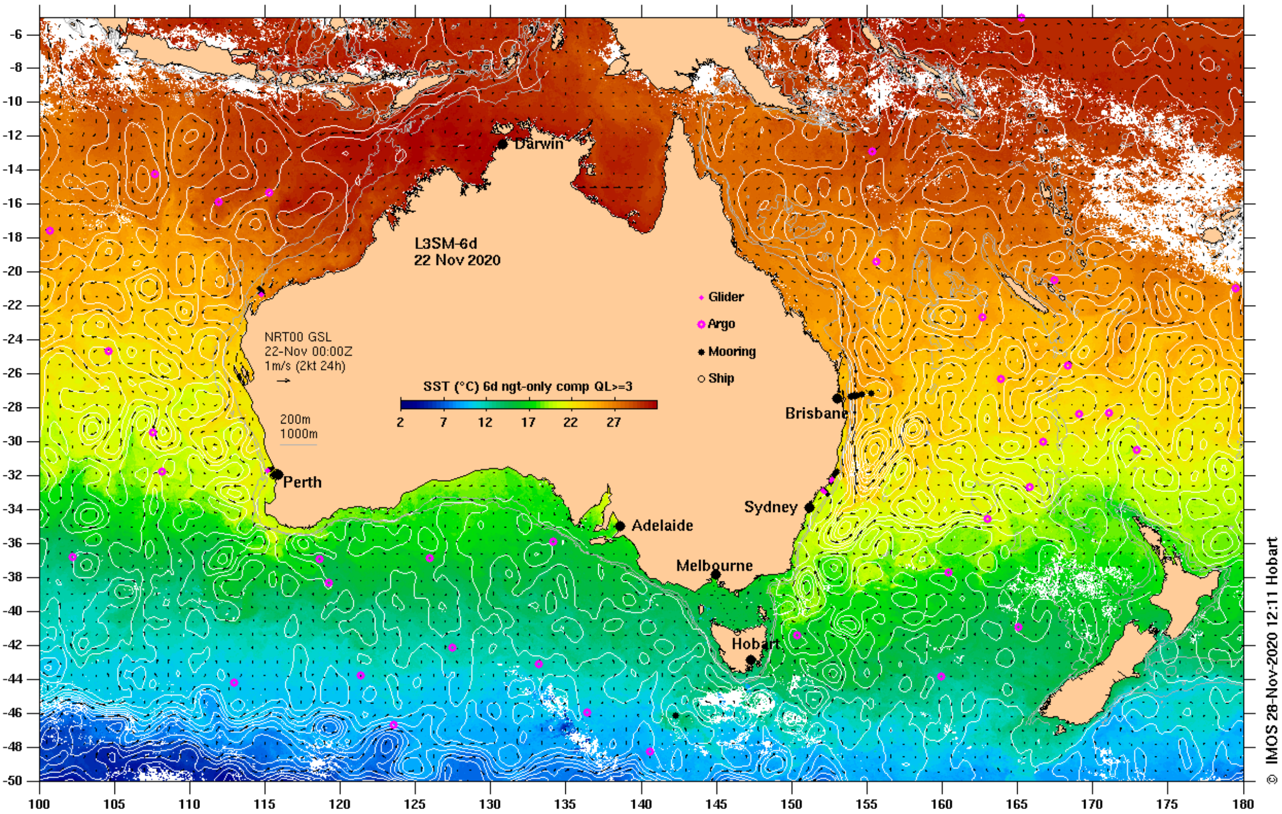

Figure 1. The environmental condition of the surface ocean surrounding Australia for 22 November 2020 illustrates the varying ocean conditions from the warm tropical oceans to the cold Southern Ocean that influence Australian climate conditions. In the figure sea surface temperature (˚C) is shown by the colour scale varying from 30˚C to 2˚C. The strong surface ocean currents, derived from satellite altimetry (vectors), shows the position of the major ocean currents: the East Australian Current along the east coast and associated eddy field in the Tasman Sea; the Indonesian Throughflow between northern Australia and Indonesia, the Leeuwin and Flinders Currents adjacent the western and southern Australian coastline, respectively. The Antarctic Circumpolar Current is identified in the southwestern corner sloping in a southeast direction across the bottom of the map. In addition, sea level anomalies (white contours) are displayed. Important components of the ocean observing system (gliders, Argo floats, moorings and ships) that the Earth Systems and Climate Change Hub utilises to advance knowledge of the ocean and its impacts on the Australian continental, coastal and regional environment are also identified.

The variability of the Australian climate is strongly influenced by the oceans that surround our island nation (Figure 1). More than 93% of the extra heat energy stored by the Earth since 1970 is found in the oceans (Rhein et al., 2013) and about 30% of human emissions of carbon dioxide have been absorbed and stored by the ocean (Rhein et al., 2013). In this way, the oceans strongly control the pace of climate change.

The ocean circulation controls where and how heat and carbon are taken up and stored on seasonal to longer time scales. The ocean circulation is responsible for the uneven global distribution of this heat and carbon, and the Southern Hemisphere oceans are a major reason for this uneven distribution. Thus, the ocean circulation impacts the spatial patterns of regional sea level change, accumulation of the warmest ocean waters north of Australia (the tropical ocean warm pools), ocean acidification, the intensity and frequency of seasonal weather extremes and marine heatwaves, and long-term climate trends.

The ESCC Hub has supported production of ocean synthesis products that underpin research, undertaken by the Hub and elsewhere, into key ocean processes of the climate system from the high-latitude Southern Ocean to the equatorial Indian and Pacific Oceans. This ocean information underpins our growing understanding of the influence of the ocean on the evolution, duration and intensity of the climate modes that dominate Australian climate seasonal variability and extremes. The improved knowledge of the ocean circulation resulting from the ESCC Hub research is vital for climate change detection and attribution studies, future projections of the climate system under emissions scenarios, and the impacts of likely future climate changes.

Box 1: Climate Quality* Ocean Observational Synthesis Products

The ESCC Hub and other NESP Hubs rely on high-quality ocean observations of temperature, salinity, carbon and other variables that are funded through a complex web of leveraged programs or ad-hoc opportunistic funds. These include significant unsecured in-kind national and international contributions . These observations provide a critical element for a host of climate research projects and mitigation and adaptation activities. These include providing initial conditions for seasonal-to-decadal prediction systems, monitoring and detecting ocean change, evaluation of the role of the ocean in major climate modes and variability of these modes, assessing variations in sea level, the Earth's energy imbalance and hydrological cycle, ocean state estimation for studying variability and change, and climate model evaluation and development. In addition, knowledge of the ocean's physical environment is fundamental to improved understanding of the ocean's biogeochemistry and biological/ecosystem variability and function.

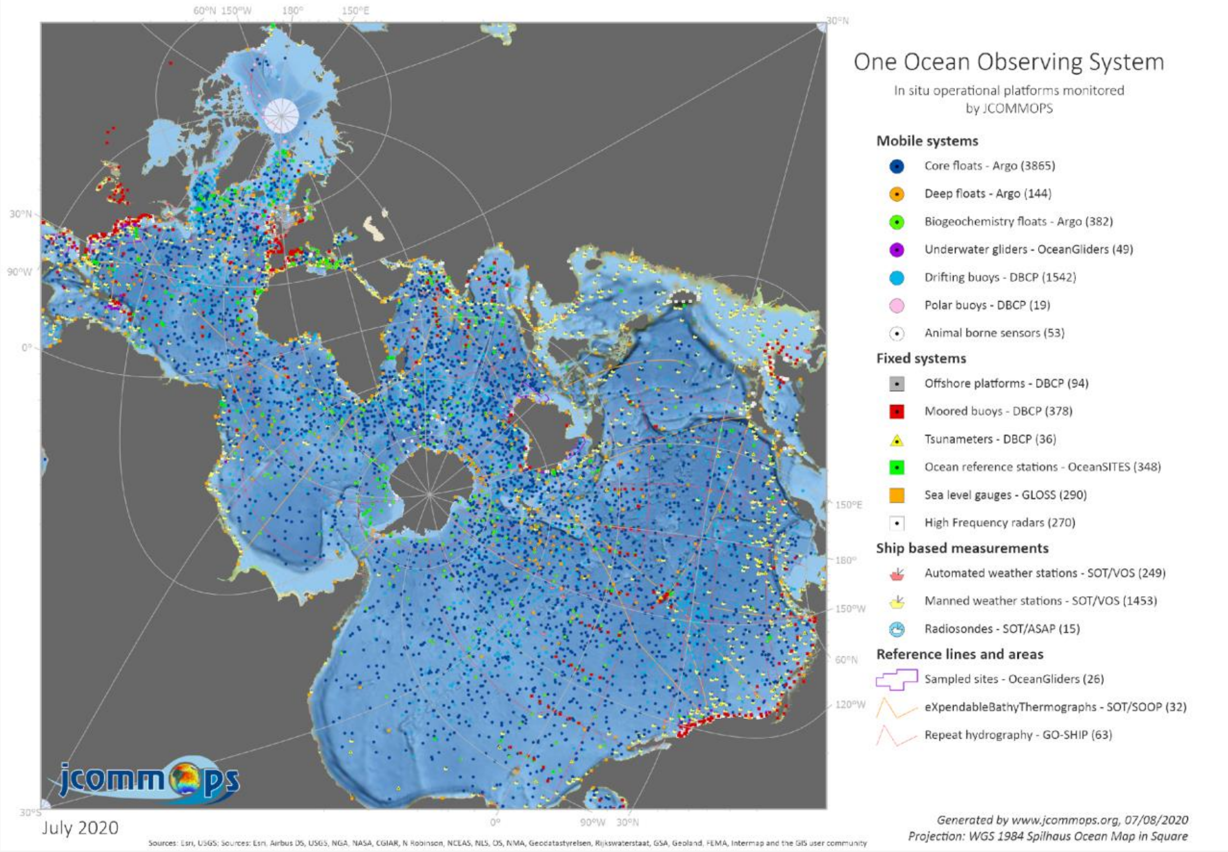

Figure B1. The heterogeneous nature of the ocean observing technology and the expanding sensors and platforms used present great opportunities and challenges for the ocean observing system. Support for coordination amongst the observational networks is vital for open and timely access to the data and delivery of higher-level derived products required by diverse user groups.

Australia has provided leadership and been a key participant in the production of high-quality ocean data sets and synthesis products relied upon by ESCC Hub researchers and the wider community. We have led the international community in the quality control procedures implemented in Argo, XBT and GO-SHIP. Examples of these efforts include the IQuOD (International Quality-controlled Ocean Database), the Argo delayed mode database and the GO-SHIP Easy Ocean gridded data product.

These routine quality-controlled products have become the definitive products used in all the prominent global reanalyses (equivalent of national meteorological office forecasts for the oceans) and underly all gridded data products from the users of the World Ocean Atlas (NOAA NCEI, Boyer et al., 2018). ESCC Hub support for Australian participation in these activities has been vital for the coordinated creation of the underlying observational product for ocean forecasting, ocean researchers, ocean decision makers and the Intergovernmental Panel on Climate Change (IPCC) assessments (including the recent IPCC Special Report on Oceans and Cryosphere in a Changing Climate).

The synthesis and delivery of higher-level derived products based upon ocean observations in support of research, operational and climate applications is a major scientific undertaking. It is only through these coordinated syntheses that integrated ocean observational datasets that meet user requirements and expand the use of the data are achieved.

*Climate quality is defined as measurements of quality sufficient to assess long term trends with a defined level of confidence.

4 Detection and attribution of climate change in our ocean environment

4.1 Ocean heat content change

The variability and change in Earth's climate are mostly driven by the energy transfer between the different components of the Earth system: ocean, atmosphere, land and cryosphere (Figure 3, Hansen, 2005; Hansen et al., 2011). The most practical way to monitor the climate state and its variability and change is to continually assess the energy in the Earth system (Hansen et al., 2011). The Earth's energy budget is a balance between incoming solar radiation and outgoing radiation. The imbalance between incoming and outgoing energy at the top of the atmosphere, due to greenhouse gas emissions, results in excess heat accumulated in the Earth system.

The ocean is a key component of the Earth's energy budget (Figure 2) as water stores over 1,000 times more heat than the air for the same temperature rise. Research under the Earth Systems and Climate Change Hub has contributed to international programs to quantify where the excess heat is stored in the ocean, determine how this heat is vertically and spatially distributed in the ocean and how it is changing through time.

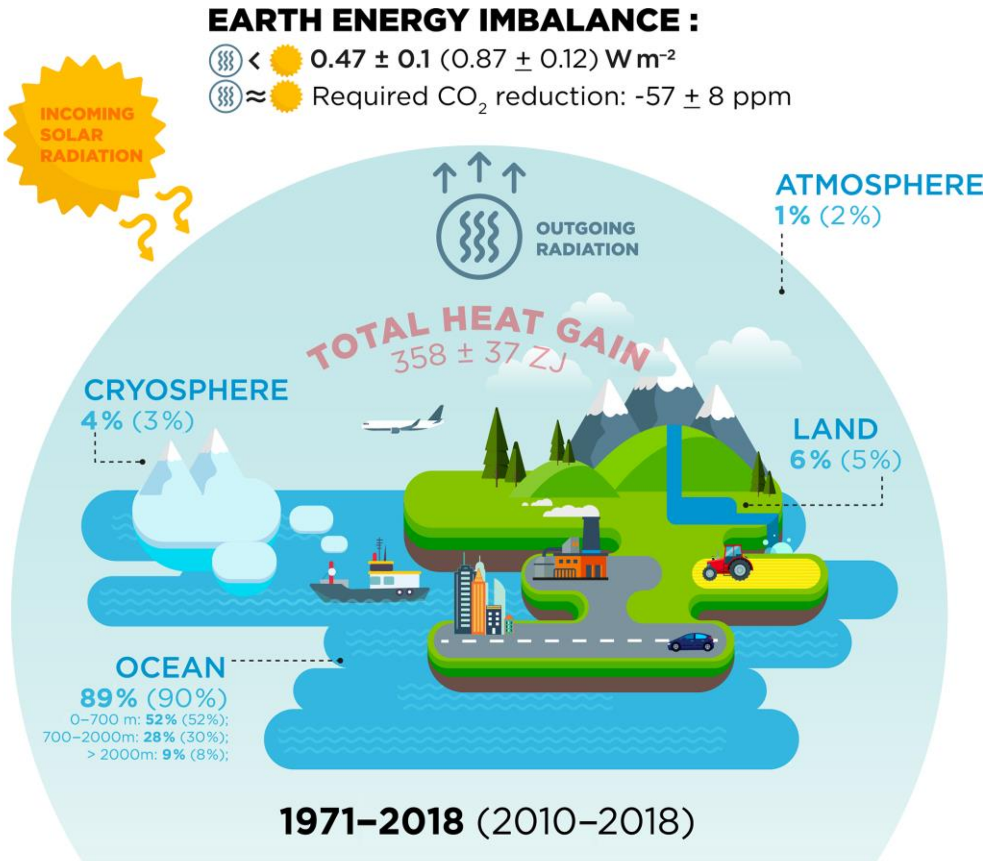

Figure 2. Schematic of where the excess heat in the Earth system due to anthropogenic climate change has been stored: the ocean has absorbed ~90% of the excess heat in the Earth system. The total heat gained by the Earth over the period 1971-2018 is obtained from observations of the ocean, land and atmosphere. The relative partitions (in %) of this heat gain into the ocean (0-700 m, 700-2000 m and > 2000 m), land, cryosphere (land ice and sea ice) and atmosphere for the periods 1971-2018 and 2010-2018 are shown. In summary, currently outgoing radiation is less than incoming solar radiation by about 0.47 W m^{-2}.To equalise outgoing and incoming radiation, we would need to reduce the concentration of CO_2 in the atmosphere by 57 ppm. (From von Schuckmann et al, 2020. This work is distributed under the Creative Commons Attribution 4.0 License)

Ocean heat uptake

Over the past few decades, ESCC Hub supported observations of the ocean have accurately measured the ocean's changing temperature, recording increases in the ocean heat content (see Box 1). This rise in ocean heat content corresponds to an uptake of over 90% of the excess heat trapped on Earth by the energy imbalance (Figure 2, Bindoff et al. 2019; Rhein et al. 2013). The remaining heat has been absorbed in part by the cryosphere, causing melting of land ice (which has absorbed about 3% of the excess heat), including Greenland and Antarctic ice sheets and glaciers, and Arctic sea ice. Heating of the land and atmosphere has absorbed the last 7% of the excess heat. Thus, our experience of climate change and its devastating impacts is less than 10% of what we would have felt if the ocean did not absorb most of the Earth's energy imbalance. Studies supported by the ESCC Hub have been critical in the detection and attribution of the magnitude, distribution and cause of the ocean heat change.

The uptake of the excess heat is not evenly distributed in the ocean. Between 1960 and 2017, the global ocean between the surface and a depth of 2000 m gained 30 x 10^{22} joules of additional heat (Bindoff et al, 2019). This is more than 60% of the heat accumulated over the full depth of the ocean. Heat absorbed at the ocean surface is redistributed both horizontally and vertically by ocean currents. As a result, the ocean is warming both near the surface and at depth (Figure 3), with the rate varying between regions and depths.

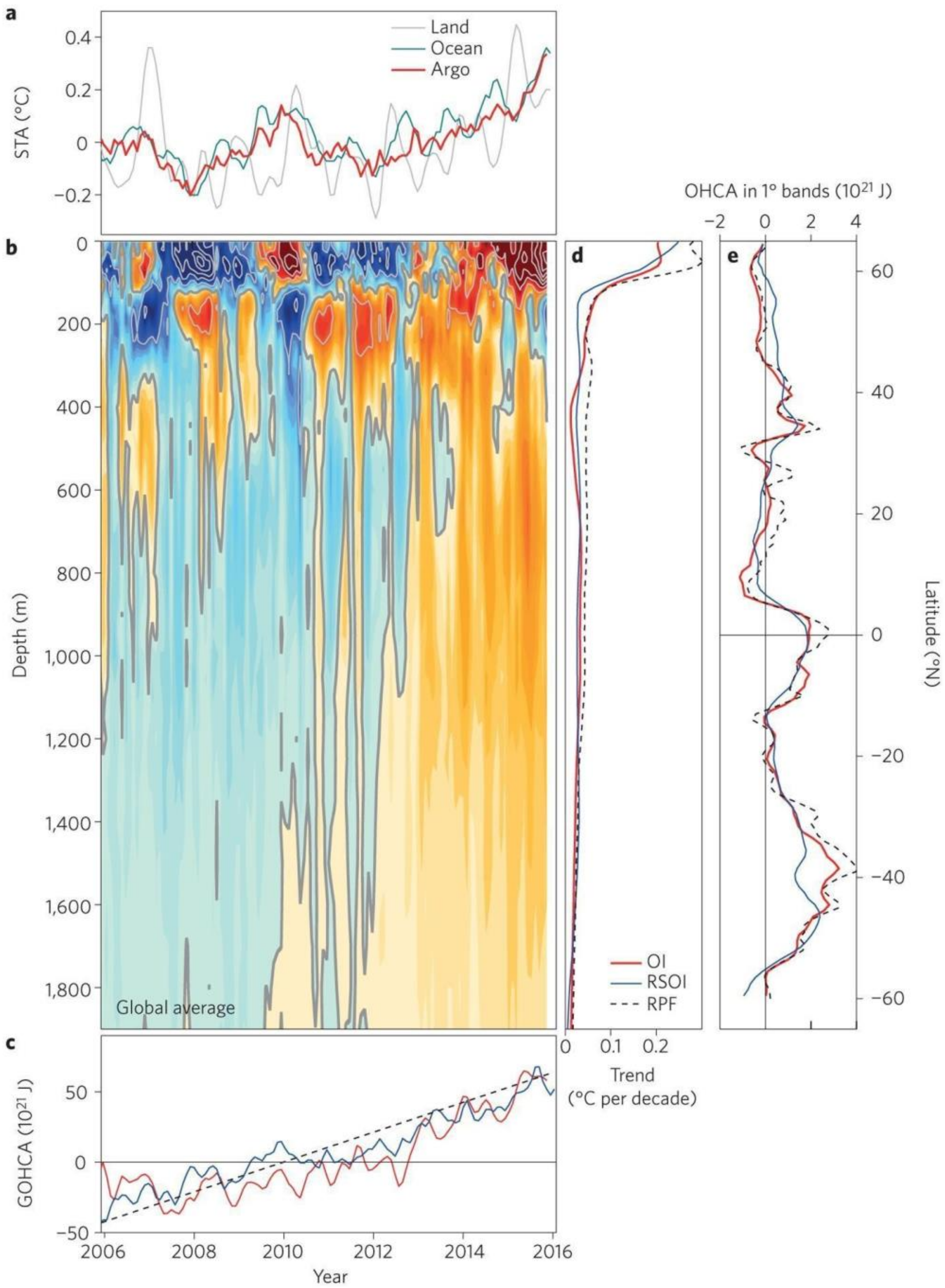

Figure 3. Ocean warming rates and distribution. a) Globally averaged surface temperature anomaly (STA, °C), from 5 m gridded Argo optimal interpolated temperature product (red), National Oceanic and Atmospheric Administration (NOAA) global ocean (blue) and a 6-month running mean of NOAA global land averages (grey). b) Global average ocean temperature anomalies from the gridded Argo product (contour interval is 0.01 for colours, 0.05°C in grey). c) Global ocean 0–2,000 m heat content anomaly (GOHCA) as a function of time, with 4-month running mean applied to the Argo-derived climatology. d) Global average 2006–November 2015 potential temperature trend (°C per decade) and e) the zonally integrated heat content trends in 1° latitude bands, showing highest heat uptake near 40ºS. (From Wijffels et al., 2016).

The Southern Hemisphere oceans account for 67–98% of the total ocean heat increase in the uppermost 2000 m of the ocean (Wijffels et al. 2016, Bindoff et al. 2019, Rathore et al. 2020a, 2021). The most significant upper 700 m warming occurred in the large extratropical and polar band between 30ºS–60ºS. Due to the location of currents that move water, the heat gained in the Southern Ocean circulates into the Indian, Pacific and Atlantic Oceans. Warming of the Southern Hemisphere subtropical gyres is driven, in part, by an intensification of Southern Ocean winds in recent decades, facilitating the penetration of heat to deeper ocean depths.

ESCC Hub research has identified a new mechanism for the redistribution of heat in the ocean that has led to the current dominance of the Southern Hemisphere oceans in global heat uptake (Rathore et al. 2020a, 2021). This finding identifies, for the first time, a large-scale intrinsic ocean mode that concentrates ocean warming in one hemisphere at a time. Recently, most of the increase in ocean heat content has been in the Southern Hemisphere oceans, while the northern basins have remained steady or even slightly cooled. ESCC Hub researchers have shown that this hemispheric asymmetry in ocean warming is due to a previously unknown cycle called the Asymmetric Mode. This cycle appears to be changing sign with a slowing of the recent Southern Hemisphere dominance in ocean heat uptake and an acceleration in ocean warming in the Northern Hemisphere (Rathore et al. 2020a). Furthermore, ocean model experiments have shown that the simulated Southern Ocean heat uptake is sensitive to the model's vertical resolution at the surface. These findings offer guidance for examining Southern Ocean heat uptake and storage in future modelling studies and observations.

The Asymmetric Mode shifts the location of ocean warming in response to anthropogenic climate change, delivering increased heat. While we have detected the footprint of the Asymmetric Mode in observations and models and we know the pathway for the movement of heat are ocean currents and the global overturning circulation (Figure 6), further work is needed to fully understand this phenomenon

ESCC Hub-led studies have shown that Southern Hemisphere warming below 2000m dominates the global signal in the deep ocean (Figure 4). The largest warming trends are observed in deep basins adjacent to the Antarctic continent (Van Wijk and Rintoul, 2014). Significant warming has also occurred in the connected Indian and Pacific deep basins (Figure 4; Purkey and Johnson, 2010; Sloyan et al., 2013, Purkey et al, 2019).

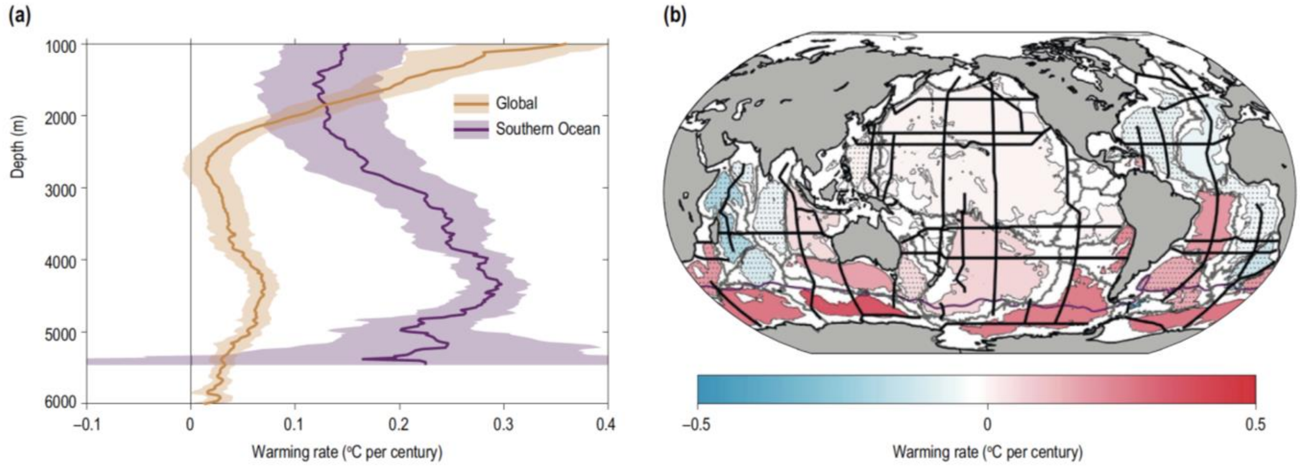

Figure 4. Observed rate of deep ocean warming as a function of (a) depth and in the (b) deep ocean below 4000 m. The comparison of the average deep ocean warming vertical profile for the global ocean and Southern Ocean shows that below 2000m the Southern Ocean warming exceeds the global average by an order of magnitude. The ability of the ocean to store the excess heat in the deep ocean is critically dependent on Southern Ocean bottom water mass formation processes and circulation pathways. The areal extent of the Southern Ocean warming is shown in (b). The black lines in (b) show the repeat hydrographic sections maintained by GO-SHIP used to estimate the deep ocean warming trends (From Bindoff et al., 2019).

The detection of long-term warming and stratification change of the deep ocean is based on high quality, but limited, temporal data. More recently, ESCC Hub researchers using higher temporal resolution observations documented the interannual variability of the deep ocean properties (Castagno et al., 2019; Silvano et al. 2020). The ocean observations document a recovery in the salinity, density and thickness of Antarctic Bottom Water (AABW) formed in the Ross Sea, with properties in 2018–2019 similar to those observed in the 1990s. The recovery was caused by increased sea ice formation on the continental shelf. The cause of the increased sea ice formation was found to be due to anomalous wind forcing associated with the unusual combination of positive Southern Annular Mode and extreme El Niño conditions between 2015 and 2018 (Figure 5). This work highlights the sensitivity of AABW formation to remote forcing and teleconnections between ENSO and SAM and shows that climate anomalies can drive episodic increases in local sea ice formation that counter the tendency for increased ice-sheet melt to reduce AABW formation.

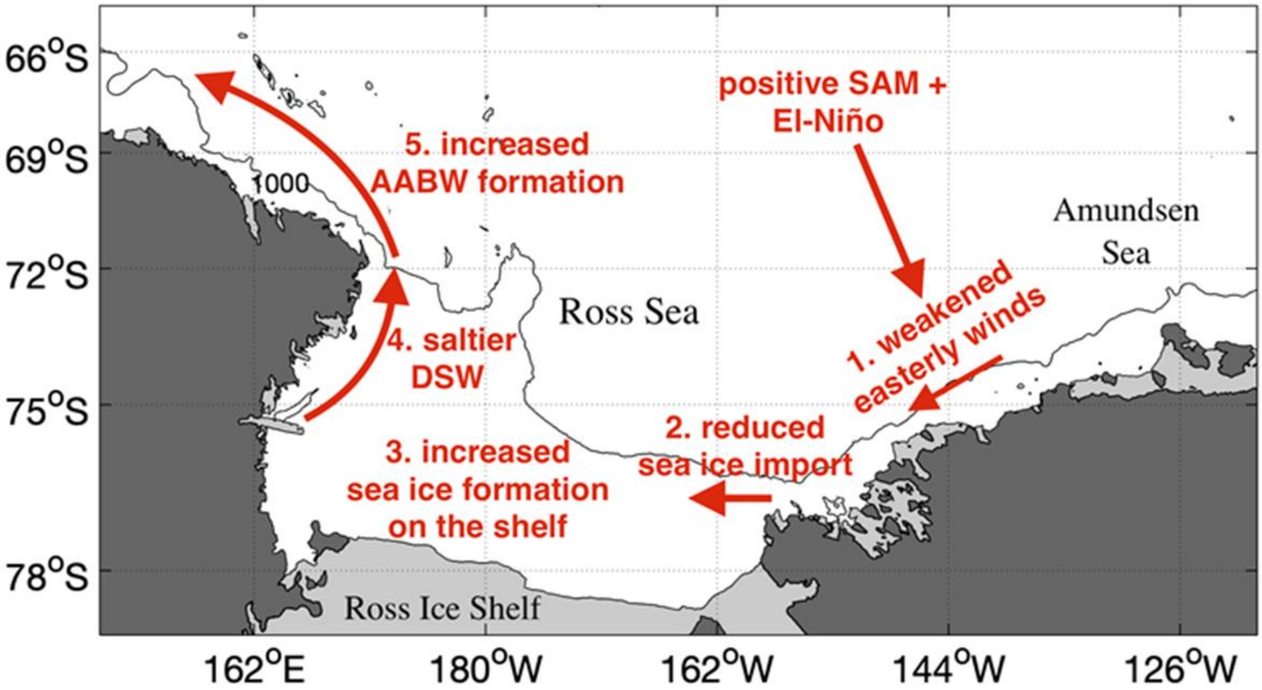

Figure 5. Schematic showing the link between climate modes and the variability of deep water formation in the Ross Sea. The unusual combination of positive SAM and El Niño resulted in weaker easterly winds in the western Amundsen Sea, less import of sea ice and a more open sea ice pack with higher rates of sea ice formation on the Ross Sea continental shelf. The resulting increase in dense shelf water (DSW) salinity enhanced the formation of Antarctic Bottom Water (AABW). The 1,000-m isobath is highlighted to visualise the margin of the continental shelf. (From Silvano et al., 2020).

Modelling ocean heat content

Earth system model estimates of ocean heat uptake are consistent with the observationally based estimates over the same time-periods. Model-based attribution studies have shown that the global ocean heat content changes are due to human activity (Bindoff et al., 2013, Gleckler et al. 2016). However, there remain large biases in the model vertical and horizontal distribution of ocean heat content compared to the observational-based studies.

To tackle the persistent model heat-uptake biases, ESCC Hub researchers developed a set of perturbation experiments to explore the influence of both model vertical and horizontal resolution on the simulation of ocean heat uptake (Stewart and Hogg, 2019). The simulations and analysis from this study demonstrate a number of important points:

- that the surface wind speed, wind stress and wind stress curl are sensitive to the vertical resolution at the ocean surface;
- that the surface momentum fluxes and associated upwelling can change from a purely thermal forcing perturbation;
- that the position of the zero wind stress curl is critical to determine which regions experience an increase or decrease of heat when the system is perturbed;
- that increased rates of heat uptake can occur with relatively coarse vertical resolution at the ocean surface; and
- that the upwelling branch of the Southern Ocean circulation is enhanced when going from 1° to 0.25° resolution.

This work clearly shows that model-simulated Southern Ocean heat uptake is sensitive to the vertical resolution at the surface; simulations with relatively coarse surface resolution (10m) exhibit heat content changes at rates nearly double that of simulations with finer surface resolution (1m). These findings offer guidance for examining Southern Ocean heat uptake and storage in future modelling studies and observations.

Box 2: Earth System Model Development

Numerical models are fundamental tools in climate research. They range from very detailed models of a particular process to complex global and regional climate or Earth system models, to more idealised climate system models. They are used in a wide variety of applications including studies of processes, data assimilation and analysis, attribution, historical and paleo-climate simulation, seasonal to interannual climate prediction, future climate projections and regional downscaling. Additionally, climate services and related information used for societal and policy purposes are largely based on the output of such models.

The continued improvement of numerical models to enable more reliable climate predictions and projections relies on the systematic assessment of models and development of parameterisations of dynamical processes not explicitly represented in the model. A significant contribution to enable international model intercomparison projects is the development of community-agreed forcing fields for both Earth system models and/or ocean or atmosphere-only models. Australia led efforts to identify suitable repeat year forcing fields from the Japanese 55-year atmospheric reanalysis (JRA-55) (Stewart et al., 2020). This process identified three repeat-year forcing periods of the JRA-55 suitable for multi-model assessment projects. These suggestions have been endorsed by the international modelling community.

The ESCC Hub relies heavily on the implementation and assessment of model development undertaken by the Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA). COSIMA is comprised of a number of universities (ANU, UNSW, UTAS) and publicly funded research agencies (BoM, CSIRO and AAD) and is supported by the National Computational Infrastructure, the Australian Research Council and the ESCC Hub. COSIMA is at the forefront of development of the ocean-sea ice component of the Australian Community Climate and Earth-System Simulator (ACCESS) model, Australia’s national climate model.

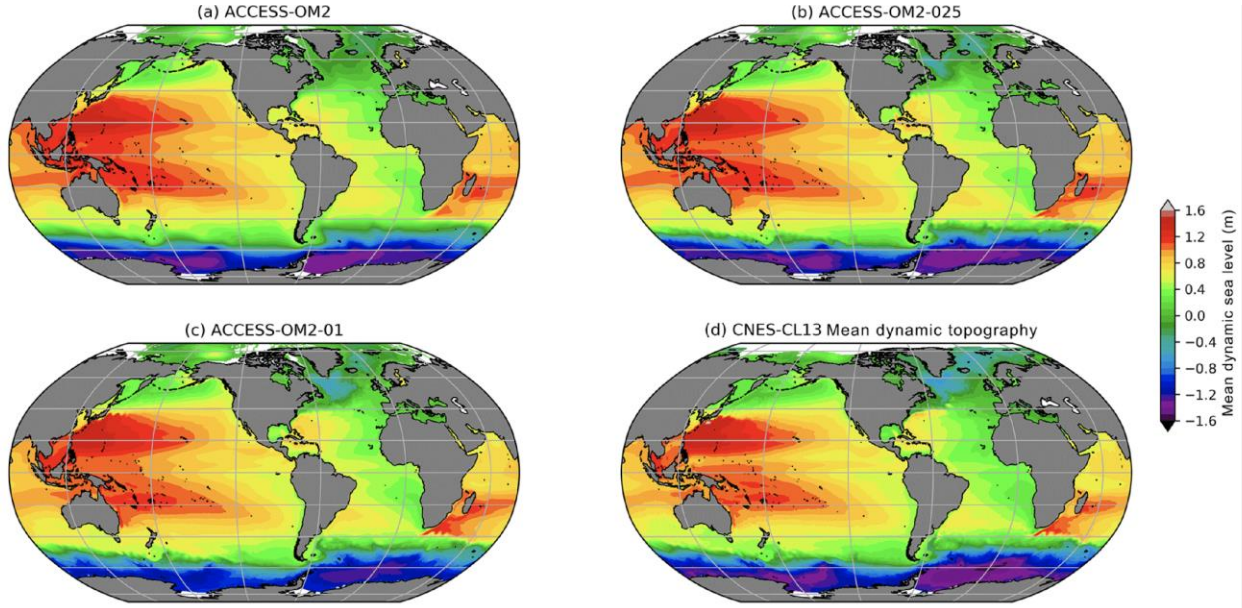

Figure B2. Example of outputs from a range of numerical ocean models (OM). The 1993-2012 mean dynamic sea level in (a) ACCESS-OM2, (b) ACCESS-OM2-025 and (c) ACCESS OM2-01. (d) Observational reconstruction of 1993-2012 mean dynamic topography from satellite altimetry. The model outputs have had a 0.5 m offset added for clarity. (From Kiss et al, 2020).

Regional variations in ocean heat content

While the oceans have warmed overall, there is regional variability in the magnitude and even sign of the change. For example, the surface ocean close to Antarctica has actually cooled, despite warming of the overlying atmosphere. This surface cooling is in part caused by the release of fresh water from melting ice that can both cool the surface layer and warm the subsurface waters that access ice shelf cavities (Silvano et al., 2018; Bronselaer et al., 2018).

The Tasman Sea warming rate is two to three times faster than the global mean surface ocean warming rate (Wu et al., 2012). This warming is linked to changes in South Pacific wind fields and the circulation pathways of the East Australian Current (Ridgeway 2007; Hill et al., 2011; Sloyan and O'Kane 2015).

ESCC Hub research has shown that warming of the western Pacific has changed the behaviour of El Niño. Historically, El Niño tends to originate in the eastern Pacific. Its origin is shifting to the western Pacific and is increasing the strength of El Niño events. A redistribution of heat from the western Pacific to the Indian Ocean, via the Indonesian Throughflow, is estimated to have played a key role in regulating global mean surface temperatures, with the Indian Ocean representing about one quarter of the global ocean heat gain since 1990 (Sprintall et al., 2019, Beal et al, 2020, and references therein).

4.2 Ocean circulation variability

Ocean warming coupled with changes to the wind forcing results in observable changes in the ocean circulation. Research under the ESCC Hub has identified ocean circulation variability in the Southern Ocean, Pacific and Indian Oceans and the potential impact of and on the major climate modes.

The Antarctic Circumpolar current

The world's largest ocean current, which is found in the Southern Ocean, is the Antarctic Circumpolar Current (ACC). The ACC flows from west to east around the Antarctic continent. At its northern boundary the Southern Ocean connects to the large sub-tropical gyres of the Indian, Pacific and Atlantic Oceans where the narrow strong 'western boundary currents' (such as the East Australian Current) transport heat, salt, carbon and nutrients to the Southern Ocean.

Researchers in the ESCC Hub have shown that the Southern Ocean connects the atmosphere and the surface ocean to the deep interior of the ocean. The ocean is stratified (layered), with light water near the surface and denser water below (see Antarctic Climate & Ecosystems Cooperative Research Centre, 2019 for more details). However, the light and dense layers are not flat. The ocean layers are tilted by ocean currents, and stronger current flow occurs where the tilt is steeper. The deep, strong flow of the ACC coincides with tilted density layers by thousands of metres over the width of the current (Figure 6).

Deep water spreads southwards across the ACC and upwells to the sea surface near Antarctica. Some of the upwelled water sinks again as cold, dense Antarctic Bottom Water. This is the densest water mass in the world's oceans, and it sinks to the deepest layers of the ocean. The rest of the upwelled deep water is made less dense by warming and freshening at the sea surface while being driven north again across the ACC by the westerly winds. These surface waters ultimately sink again north of the ACC and circulate northward into the Indian, Pacific and Atlantic Oceans. These two counter-rotating vertical cells form the global overturning circulation that drives the storage of heat and carbon dioxide in the deep ocean.

The vigorous overturning circulation in the Southern Ocean acts like a conveyor belt, sweeping heat and carbon absorbed by the surface ocean first northwards and then downwards into the ocean interior of the Atlantic, Indian and Pacific Oceans (Figure 6). Consequently, the extent to which the ocean slows or accelerates the pace of climate change strongly depends on processes at work in the Southern Ocean and the ocean circulation in the adjacent Atlantic, Indian and Pacific Oceans.

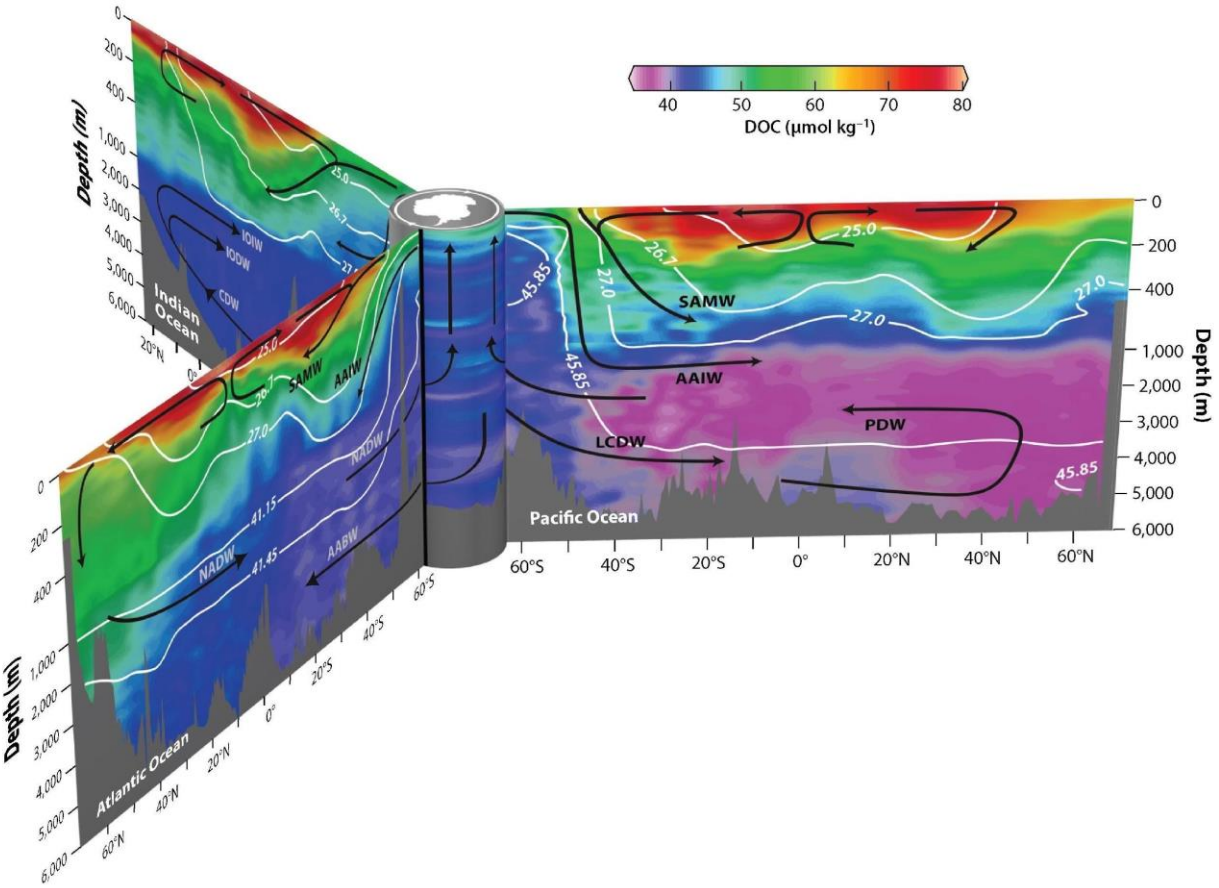

Figure 6. Schematic of the global ocean overturing circulation. This is dominated by processes occurring in the Southern Ocean and high-latitude North Atlantic (black arrows) and the distributions of dissolved organic carbon (DOC) in the Atlantic, Pacific, and Indian Oceans along GO-SHIP repeat hydrography transects. Arrows depict water-mass renewal and circulation; white lines indicate sloping density surfaces. In the Pacific, there is a northward invasion of relatively DOC-enriched Circumpolar Deep Water along the bottom, slow removal of DOC into the far North Pacific, and return flow of DOC-impoverished water to the south at mid-depths. Abbreviations: AABW, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; CDW, Circumpolar Deep Water; DOC, dissolved organic carbon; GO-SHIP, Global Ocean Ship-Based Hydrographic Investigations Program; IODW, Indian Ocean Deep Water; IOIW, Indian Ocean Intermediate Water; LCDW, Lower Circumpolar Deep Water; NADW, North Atlantic Deep Water; PDW, Pacific Deep Water; SAMW, Subantarctic Mode Water (From Talley et al., 2016).

Understanding impacts on the Antarctic Ice Sheet

Research under the ESCC Hub has explored new ocean observations that have provided further evidence of the potential vulnerability of the Antarctic Ice Sheet. The East Antarctic ice shelves have long been thought to be more isolated from warm ocean waters than those in West Antarctica, and therefore the East Antarctic Ice Sheet was thought to be more stable. Given that more than 90% of the Antarctic ice volume is in East Antarctica, this was reassuring. However, an expedition in 2015 showed that at least some parts of East Antarctica are also exposed to warm ocean waters. The expedition, led by ESCC Hub researchers, was the first to reach the front of the Totten Glacier and collect oceanographic measurements. These showed that relatively warm water was flowing strongly into the ice shelf cavity through a deep trough at the front of the ice shelf (Rintoul et al., 2016). The warm water was melting the ice shelf rapidly from below, producing fresh meltwater that was observed to be flowing out of the ice shelf cavity. This research shows that estimates of future sea-level rise need to include the potential contribution from East Antarctica.

Overall, enough ice has been lost from Antarctica over the past quarter-century to raise global sea level by 8 millimetres (Antarctic Climate & Ecosystems Cooperative Research Centre, 2019). The acceleration in loss of ice from Antarctica has been linked to increased melting of ice shelves by warm ocean waters.

More than 90% of the Antarctic ice volume is in East Antarctica, with some parts of East Antarctica exposed to warm, deep ocean waters.

The East Australian Current

In the poleward pathway, which completes the loop of the South Pacific Ocean gyre circulation, large quantities of heat are transported southward in the East Australian Current (EAC). The main core of the EAC separates from Australia with some flow moving eastward into the Tasman Sea and the remainder flowing southward as the EAC Extension. This separation of the EAC gives rise to a region of intense eddy activity and air-sea exchanges in the Tasman Sea, with marked influence on climate over Australia and New Zealand. Part of the EAC extension forms the Tasman Outflow that connects the South Pacific subtropical gyre with the Indian Ocean, forming a supergyre that redistributes water and heat amongst the Indian, Pacific and Atlantic basins (Ridgway and Dunn, 2007).

At mid-latitudes, multi-decadal changes in basin-scale wind fields are occurring (Roemmich et al. 2016). The ocean circulation is already responding to these changes in wind forcing, but not in the expected way. Roemmich et al. 2016 find a 5 Sv (1 Sv = 10^6 m^3 s^{-1}) increase in northward transport in the eastern limb of the South Pacific gyre that is largely balanced by increased transport at the southern gyre boundary, implying a spin up of the Pacific gyre. The increase in the transport of the equatorward and southern branches of the gyre circulation implies an increase in the poleward transport of the East Australian Current (Oliver and Holbrook, 2014). However, the gyre appears to be currently in a transitional circulation and has not reached equilibrium. Indeed, evidence suggests that none of the western boundary currents are strengthening with basin-scale wind stress changes but instead there is an enhancement in the variability and mid-latitude eddies generated from these currents (Beal and Elipot, 2016; Ganachaud et al., 2014; Sloyan and O'Kane, 2015, Oliver and Holbrook, 2014). In the East Australian Current this results in changes to the division of EAC water to either the EAC-extension or Tasman Front, but not the strength of the EAC jet.

Indian Ocean

The Indian Ocean is a significant driver of the Australian climate. ESCC Hub researchers have played a prominent role in a recent international review of the Indian Ocean Observing System and future observing needs (Beal et al., 2020), and have tackled key science challenges.

A major focus of ESCC Hub led research has been on providing improved understanding of the ocean-atmosphere coupling of the Indian Ocean. In the Indian Ocean, analysis of the mixed layer temperature budget has identified long-lived ocean interior features that propagate from Australia to Africa that substantially modify the near-surface ocean properties and induce significant fluxes of heat into the atmosphere (Chapman et al 2019). These heat fluxes can drive a coherent atmospheric response, although this response does not appear to feedback onto the ocean. This air-sea interaction mechanism provides a way for the mid-latitude ocean to influence the state of the tropical atmosphere and offers the potential for improved seasonal to decadal predictability of the tropical atmosphere.

The southeast Indian Ocean is a region where the ocean loses a lot of heat to the atmosphere. ESCC Hub research has found that the amount of heat stored in the surface mixed layer of the mid-latitude Indian Ocean is primarily the result of a balance between heat fluxes across the air-sea interface and cooling of the surface ocean by mixing with deep water below (Cyriac et al., 2019). The heat transported by the ocean currents is highly impacted by eddies and waves propagating from the coast of Western Australia, and at times also contributes to the heat balance in this region. The results of this study improve our understanding of how heat moves between the ocean and atmosphere to affect our climate and will help refine computer model projections of future climate change.

ESCC Hub researchers have shown that sea surface salinity variability in the tropical Indian and Pacific Oceans can be used as a measure of terrestrial precipitation on interseasonal to interannual time scales, and to locate the source of moisture that drives Australian rainfall (Figure 8; Rathore et al., 2020b, 2021). Novel seasonal composites of sea surface salinity during El Niño–Southern Oscillation/Indian Ocean dipole clearly show the relationship between sea surface salinity variability and atmospheric moisture transport toward and away from the Australian continent. This work has demonstrated that observations of sea surface salinity variability can aid the prediction of Australian rainfall.

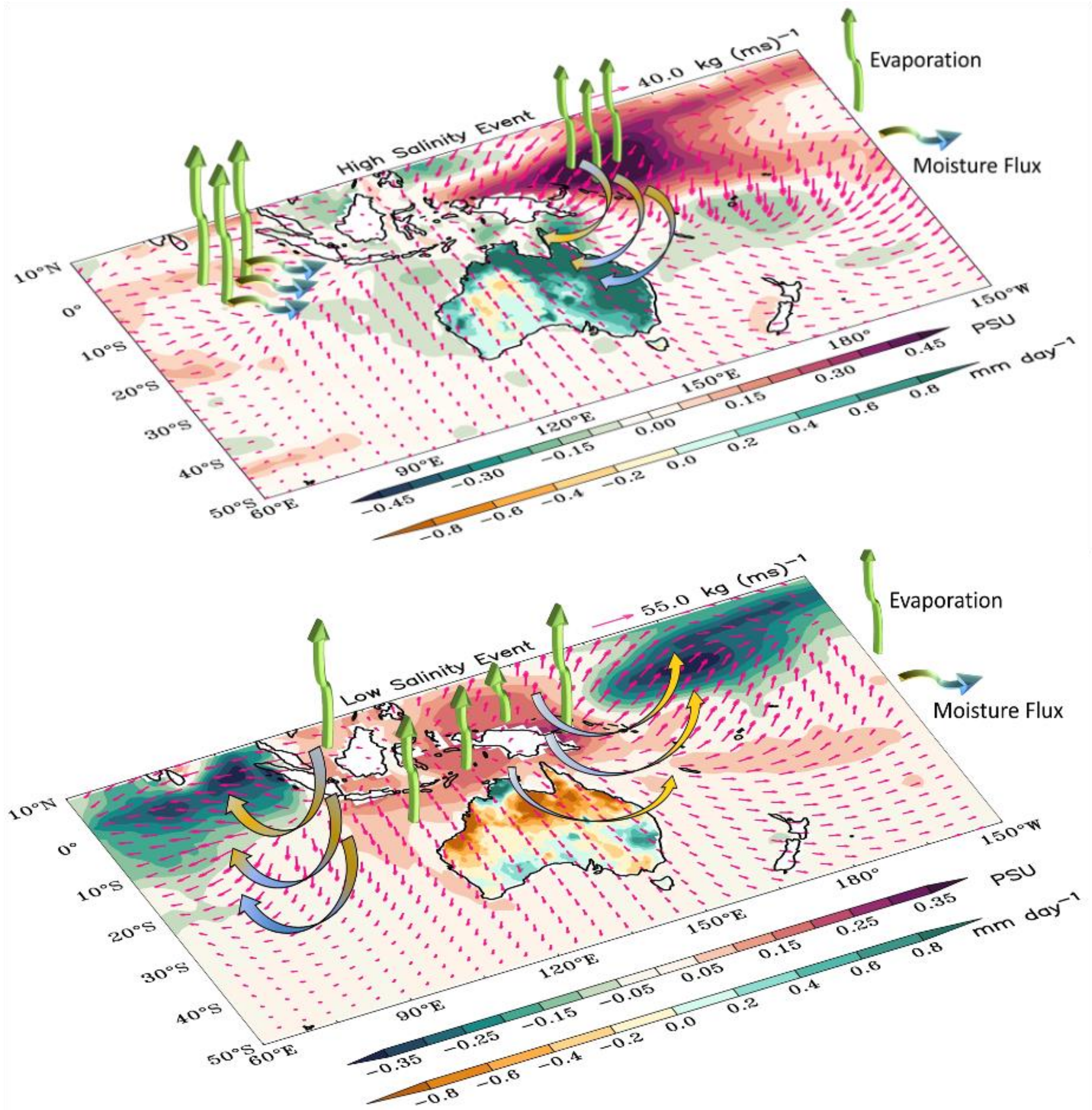

Figure 7. Schematic relationship between (a) high and (b) low sea surface salinity variability in the Indo-Pacific warm pools and rainfall over Australia. In a), high-salinity in the Indian and Pacific Oceans around 10°S–10°N coincides with high evaporation (green arrows). This extra moisture in the atmosphere (multi-coloured arrows) is transported toward Australia delivering rainfall across the land and freshening the surrounding ocean. In b), low salinity in the equatorial Indian and Pacific Oceans is the result of excess rainfall from moisture drawn from the oceans north of Australia, increasing salinity there. Australia experiences reduced rainfall (Rathore et al., 2020; 2021).

4.3 Small-scale ocean processes

The consequences of changes to the ocean vertical temperature and salinity distribution is increased ocean stratification that has a profound impact on ocean mixing. Turbulent mixing is important for the uptake and redistribution of heat, carbon, nutrients, oxygen and other properties that are carried along with the flow of water in the ocean (MacKinnon et al. 2017). Ocean mixing is therefore a key process regulating ocean circulation and climate.

ESCC Hub researchers have made a significant contribution to the investigation of the role small scale ocean processes play in regulating changes to the larger scale ocean circulation and the observational methods used to detect ocean mixing (Polzin et al, 2014). In this context, small-scale means spatial variations on the order of 1km horizontally, 100m vertically and time scales on the order of hours.

These small-scale processes are extraordinarily difficult to measure, are intermittent and sporadic, yet have significant consequences on the ocean's ability to continue to mitigate the effect of climate change and variability at regional and local scales. New modelling experiments by the ESCC Hub with the ACCESS climate model (ACCESS-OM2 suite) have provided insight into the nature of small-scale interactions between ocean and atmosphere, and how these interactions influence the heat and momentum uptake of the Southern Ocean. Specifically, it is the structure of the winds that sets the distribution of the heat uptake. The effect of wind stress on heat uptake in an ocean model is strongly dependent on the vertical resolution (Stewart and Hogg, 2019).

Research by the ESCC Hub, using both observations and models, indicate that turbulent mixing in the ocean is not constant in space or time, with mixing estimates varying by several orders of magnitude throughout the ocean (Meyer et al 2015, Cyriac et al. 2020). Interaction between the strong and deep reaching Antarctic Circumpolar Current with the complex Southern Ocean topography, wind forcing within the thermocline and eddies leads to the Southern Ocean being a prominent site for ocean mixing (Figure 5). ESCC Hub research has found that Southern Ocean mixing is a key controller of the strength of the global ocean's interior overturning circulation and the distribution of heat, carbon and other properties in the global ocean (Meyer et al. 2015, Yang et al., 2018).

The Southern Ocean is a prominent site for ocean mixing, which influences the distribution of ocean heat and carbon. Image credit: Bernadette Sloyan, CSIRO

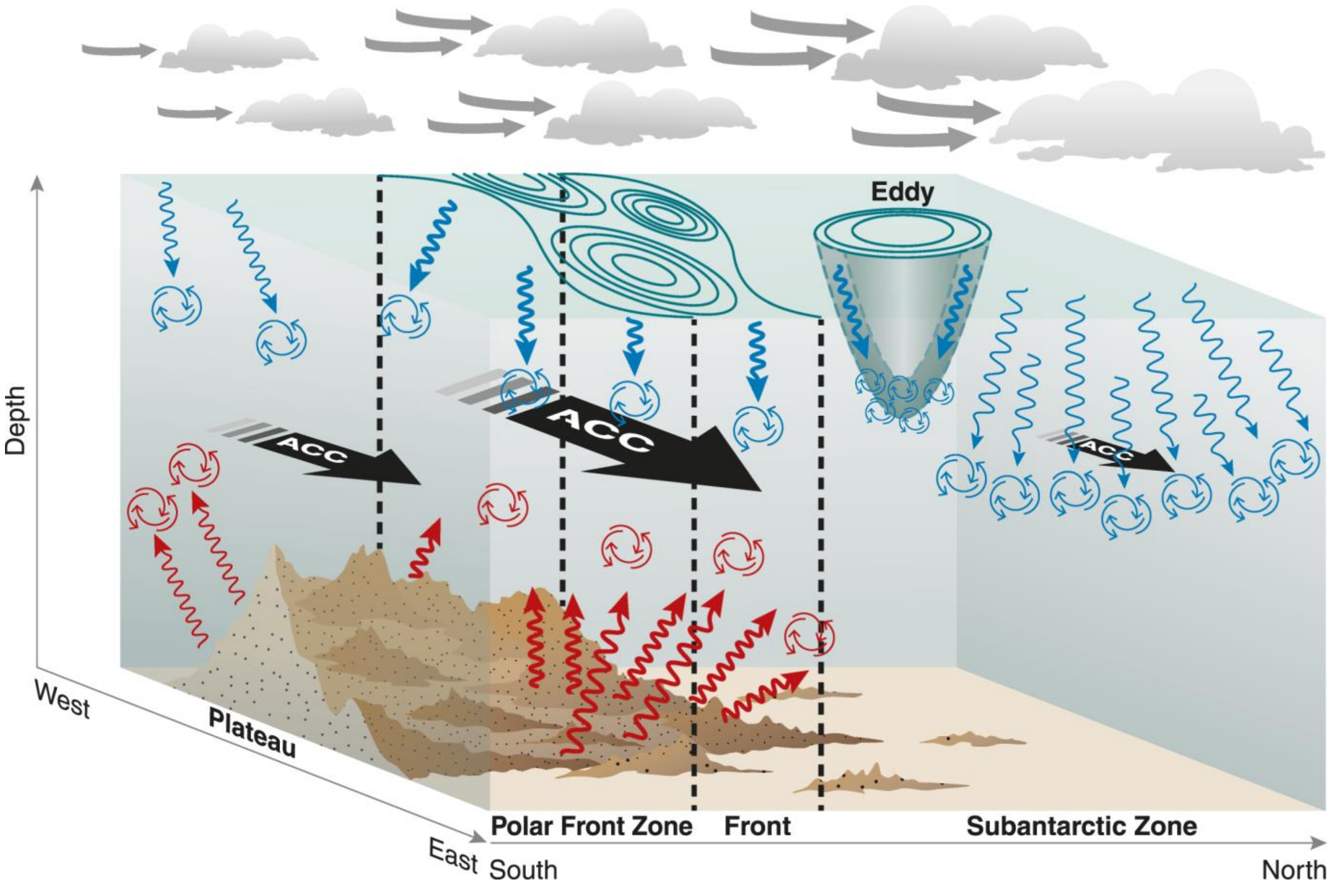

Figure 8. Schematic of the spatial distribution of ocean mixing driven by interactions between the Antarctic Circumpolar Current (ACC) and complex topography. Ocean mixing intensities are controlled by topographic roughness of the ocean bottom, generating upward-propagating internal waves (red arrows). Regions with strong flow over rough topography are associated with intense mixing values and upward-propagating internal waves that are advected away from the generation site sustaining remote mixing in the ocean interior and at ocean boundaries. In the upper ocean, stronger wind forcing generates near-inertial downward-propagating internal waves (blue arrows) that enhances ocean mixing in the upper ocean. Mesoscale eddy activity is also associated with enhanced mixing (from Meyer et al., 2015).

The ESCC Hub supported ocean studies have been hugely important in improving our knowledge of ocean variability and processes and has focussed on key science challenges relating to the Southern, Pacific and Indian Oceans. This research has provided input into major international assessment reports including the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports and Special Reports, annual World Meteorological Organization Statement on the State of the Climate reports, the CSIRO/BoM State of the Climate Reports and the Australian Government State of the Environment Assessments.

5 Ocean change driving Australian climate impacts

Research supported by the ESCC Hub has led to increased understanding of the changes and trends of the global and Australia's surrounding oceans, and their sensitivity to ongoing human-induced climate change. This work has provided a guide to what we might expect in the decades and centuries ahead (Figure 9) (Rhein et al. 2013, Bindoff et al., 2019, Rintoul et al, 2018).

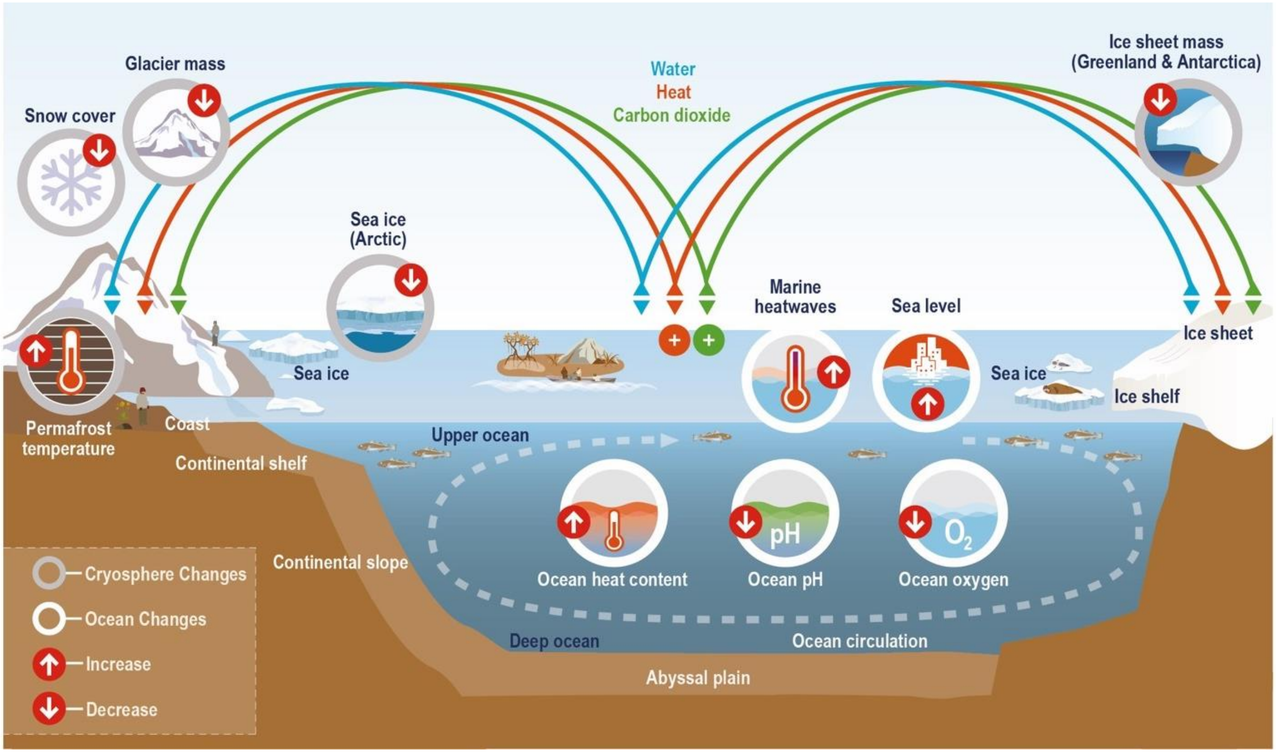

Figure 9. Schematic of the key components and changes of the ocean and cryosphere, including climate change-related effects. Linkages between components in the Earth system through the global exchange of heat, water, and carbon are shown. Climate change-related effects (increase/decrease) are indicated by arrows. Changes in the cryosphere are also shown (from Bindoff et al., Technical Summary, 2019).

Global sea level rise

The IPCC SROCC report (Bindoff et al., 2019) finds that global mean sea level rise has been accelerating. The increased ocean heat content has caused the oceans to expand (known as 'steric' sea level rise) and has contributed about 43% to the observed global mean sea level rise (Figure 10). Ocean mass contribution to sea level rise is from melting glaciers and icesheets, melting from beneath by warm ocean water. The sum of glacier (21% of sea level rise, Hugonnet et al., 2021) and ice sheet melt (33%, Oppenheimer, et al., 2019) contributions is now the dominant source of global mean sea level rise. Global mean sea level rise since 1970 is caused by greenhouse gas emissions from human activities (anthropogenic forcing, Bindoff et al. 2019).

In Antarctica, more ocean heat is reaching the floating ice shelves around the edge of, and beneath, the Antarctic Ice Sheet, driving more rapid melt and loss of ice. Measurements show that ocean heat content and ice loss from the Antarctic Ice Sheet have both accelerated in recent decades, causing an acceleration in sea level rise. At coastlines around the world, rising sea levels are increasing the probability that storm surge, or even the regular cycle of the tides, will produce sea level extremes that damage property and infrastructure and present an immediate risk to human safety. Coastal inundation may be exacerbated by damage wrought by more frequent tropical storms of increasing duration and severity, fuelled by the increasing ocean heat content (Bindoff et al., 2019).

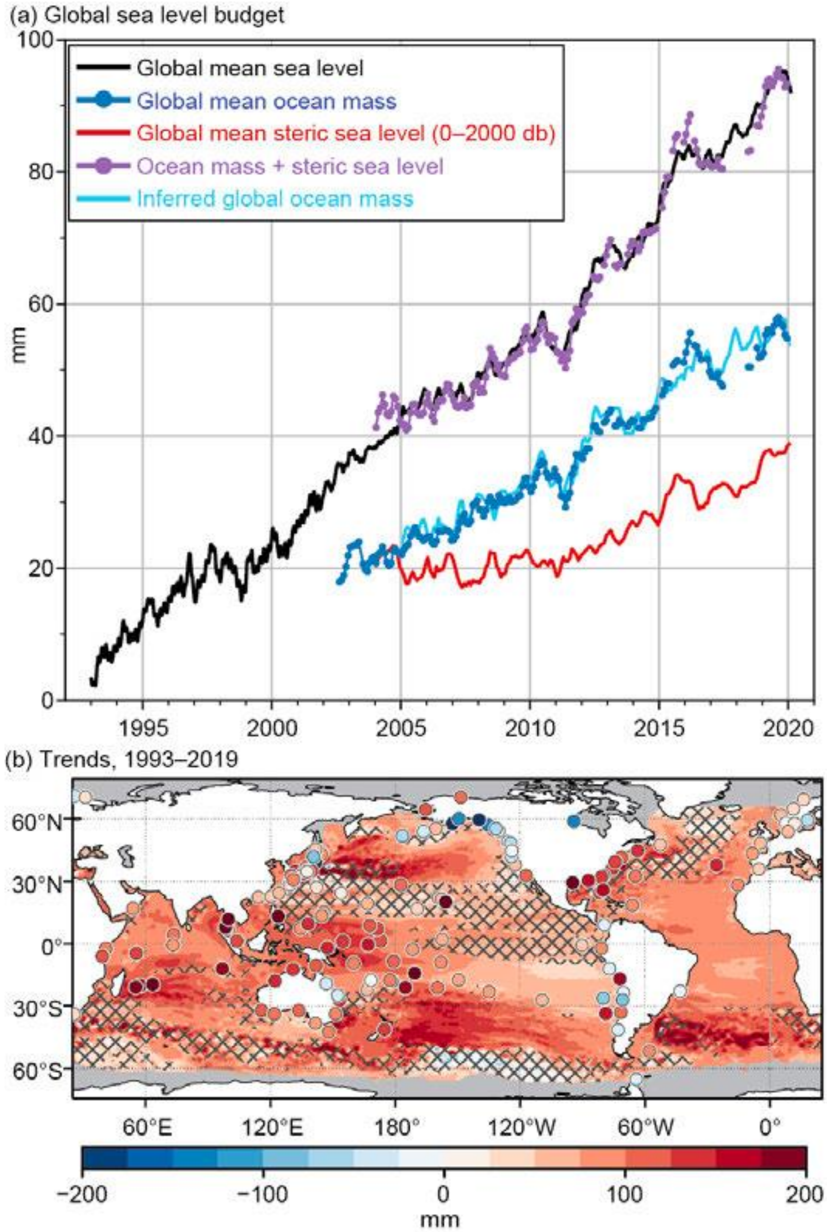

Figure 10. Global sea level and ocean mass continues to rise. (a) Monthly averaged global mean sea level rise observed by satellite altimeters (black, 1993–2019 from the NOAA Laboratory for Satellite Altimetry), global ocean mass (blue, 2003–19 from the Gravity Recovery and Climate Experiment), global mean steric sea level (red, 2004–19) from the Argo profiling float array, mass plus steric (purple), and inferred global ocean mass (cyan) calculated by subtracting global mean steric sea level from global mean sea level. All time-series have been smoothed with a 3-month filter. (b) Total local sea level change during 1993–2019 as measured by satellite altimetry (shading) and tide gauges (circles). Hatching indicates trends that are not statistically significant. (From Lumpkin et al., 2020. State of the Climate, 2019).

Sea level rise around Australia

Associated with global mean sea level rise are large regional differences in rates of sea level rise. For example, sea surface height from satellite altimetry has increased 150 mm since 1993 around Sydney, while Los Angeles has experienced just over 20 mm during that time (Lumpkin et al., 2020). Ocean circulation, indicated by regions with above global average ocean temperature increases (i.e., Tasman Sea), explains some of the heterogeneity of global sea level change.

Around Australia, the rate of sea level rise in the Tasman Sea is well above the global average (Figure 10). Changes in Tasman Sea sea levels are linked to local and regional changes in the ocean circulation, including the Pacific Ocean South Equatorial Current and East Australian Current, and are as a result of air-sea interactions. The impact of the regional sea level rise is most keenly felt through extreme sea level events, which lead to coastal flooding, inundation and erosion (McInnes et al., 2015). It is important to note that these extreme events are a result of the combined influence of the large-scale ocean circulation and local weather systems. Sea level rise at one location is linked to larger-scale regional and global ocean circulation changes, as well as to vertical land movements.

Extreme sea level events, which are linked to regional and global ocean circulation changes, can lead to coastal flooding, inundation and erosion in Australia.

El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD)

The tropical Indian Ocean and Pacific Ocean warm pools bordering northern Australia are some of the warmest waters in the global oceans, with sea surface temperatures in excess of 28°C. These warm water pools play a key role in sustaining tropical atmosphere deep-convection and maintaining the atmospheric circulation. The regional sea surface temperature variations of the tropical Pacific and Indian Oceans cause changes in the surface winds that shift the centre of deep atmospheric convection and global and regional weather patterns, subsequently altering the precipitation and ocean circulation patterns within the entire Indo-Pacific region. The intensity and changing position of these warm water pools are the drivers of the ENSO and IOD cycles (Figure B3).

In Australia, the severe droughts of 1982, 1994, 2002 and 2006 were all associated with ENSO, with severe flooding associated with La Niña events. While the potential climate impacts of ENSO or IOD are well known, the ability to provide reliable seasonal and multi-year forecasts of these events and their intensity is a key science challenge. A key knowledge gap in the quest for improved ENSO prediction is the evolution of the ocean circulation that primes the climate to move into either a positive or negative mode.

Southern Annual Mode

The Southern Annular Mode (SAM, Figure B3) is a low-frequency mode of atmospheric variability of the Southern Hemisphere that is defined as a belt of strong westerly winds surrounding Antarctica which moves north or south depending on the phase of its cycle. It is a climate driver for Australia, influencing the position of cold fronts that bring precipitation to southern Australia. Winds associated with the Southern Annular Mode cause oceanic upwelling of warm circumpolar deep water along the Antarctic continental shelf, which has been linked to ice shelf basal melt, representing a possible ocean circulation mechanism that could destabilise large portions of the Antarctic ice sheet.

SAM positive phase is associated with an intensification and contraction of the Southern Ocean westerly wind towards Antarctica. In the Australian summer, SAM positive results in increased rainfall in south-east Australia, and more frequent east coast lows, due to higher onshore flows from the Pacific Ocean. In winter, SAM positive results in decreased snow in the alpine areas and decreased rainfall in the far south and southwest. This phase occurs more frequently with a La Niña event. A negative SAM results in the westerly winds being displaced towards the equator and decreased rainfall in the southeast of Australia in the summer. In winter, wetter than normal conditions are experienced in the south and southwest, with more snowfall in the alpine areas but drier in the east coast due to less moist onshore flows from the east. This phase of SAM is usually more frequent with an El Niño event.

Box 3: Australia's key climate drivers

Australia's climate variability is governed by the large-scale coupled ocean-atmosphere climate modes of the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Southern Annular Mode (SAM), monsoons and the Madden-Julian Oscillation (MJO) - and interactions amongst these modes (Figure B3). The ocean is central to setting up these modes, their intensity and duration.

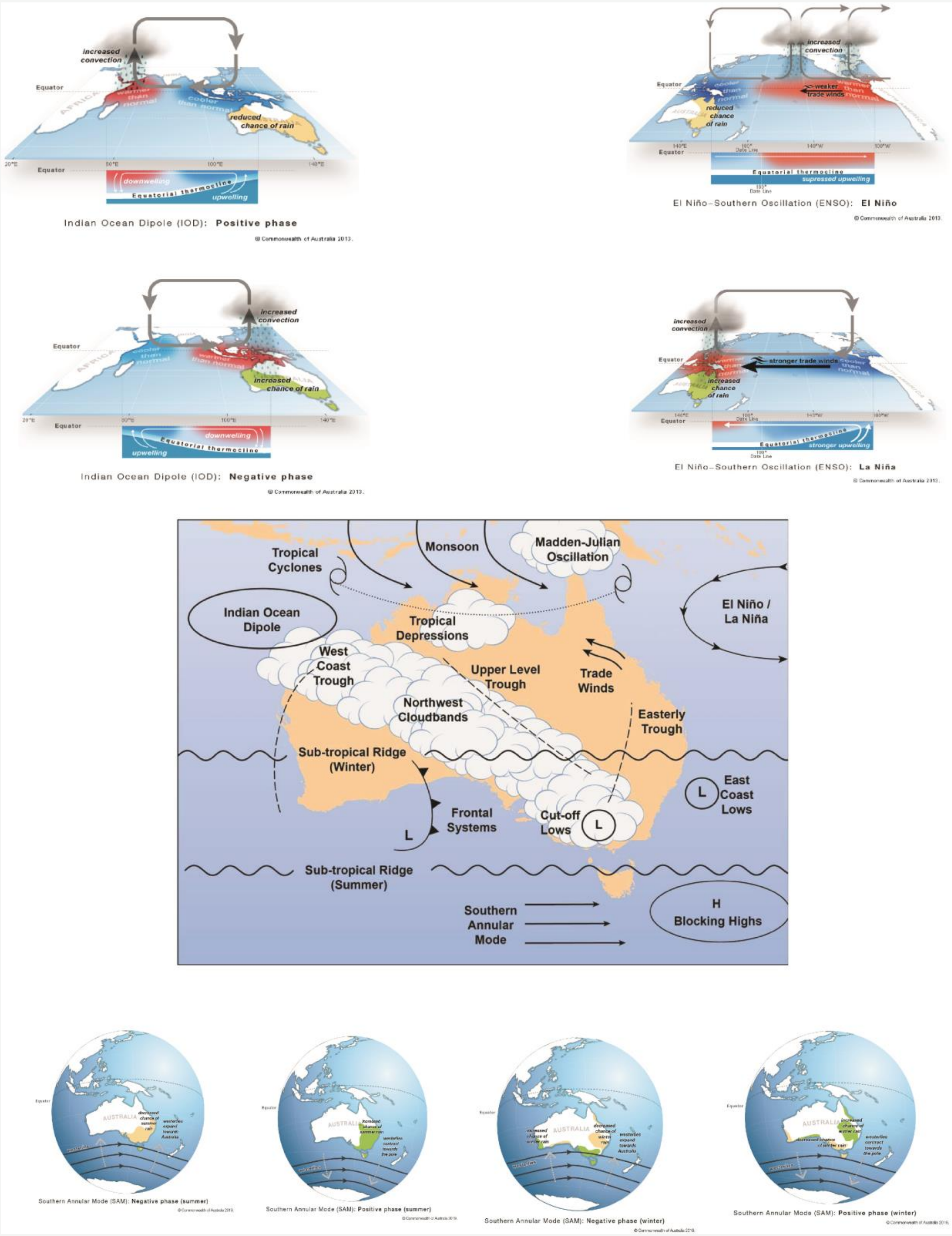

Figure B3. The major drivers of Australian climate variability. El Niño-Southern Oscillation (ENSO, top row), Indian Ocean Dipole (IOD, middle row), and Southern Annular Mode (SAM, bottom row). Compilation of climate mode schematics sourced from www.bom.gov.au/climate/about/.

Ocean impacts on key Australian climate drivers

The changing mean ocean state and its variability are drivers of many extreme climate events. The 2015/2016 El Niño can be considered as the first extreme El Niño of the 21st Century. Its magnitude is partially attributed to an unusually warm equatorial Pacific Ocean that persisted from 2014 to the event start, and the long-term background ocean warming (Santoso et al., 2017) and the dominance of Southern Ocean heat uptake since 2000 due to the Asymmetric Mode (Rathore et al. 2020a, b).

The 2015/2016 El Niño had severe impacts on the Australian climate. Australia experienced its third-driest spring on record and a record early heatwave in October. During this event, the northern wet season produced a record-low number of tropical cyclones, passing the previous low that was recorded in the extreme El Niño in 1987-88. A decrease in wet season activity resulted in fewer clouds and less tropical rain contributed to the most severe coral bleaching event on record for the Great Barrier Reef. The combination of heat and low rainfall brought a very early start to the fire season, with more than 70 fires burning in Victoria and around 55 fires in Tasmania during October 2015. Dry conditions in Tasmania also resulted in hundreds of fires being started by dry lightning in mid-January 2016. The fires damaged large areas of the Tasmanian Wilderness World Heritage Area, including areas of rainforest and bogs, which may not have seen fire for centuries.

Conversely, La Niña occurs when the western Pacific warm pool intensifies and the eastern Pacific cold tongue expands westward due to changes in the slope of the ocean thermocline resulting from stronger equatorial trade winds. The enhanced trade winds drive warm surface waters to the western Pacific and northern Australia. La Niña also results in an increase in ocean transport between the Pacific and Indian Oceans via the Indonesian Throughflow. A stronger Indonesian Throughflow warms the Indian Ocean, accelerates the Leeuwin Current off Western Australia and sets the stage for marine heat waves along the western Australian coastline that have devastated important marine ecosystems and marine industries.

During La Niña, eastern Australia generally experiences enhanced rainfall, and northern Australia can experience an early onset of the wet season. For example, in the Murray–Darling Basin, winter–spring rainfall averaged over all 18 La Niña events (including multi-year events) since 1900 was 22% higher than the long-term average, with the severe floods of 1955, 1988, 1998 and 2010 all associated with La Niña.

The duration, intensity and impact of El Niño and La Niña events is controlled by the evolution of the state of the Pacific Ocean's thermocline which involves subsurface temperature anomalies acting upon the mixed layer in the equatorial Pacific, and the anomalous zonal and vertical ocean circulation in the tropical Pacific Ocean (Santoso et al., 2017).

In the Southern Ocean, the Southern Annular Mode (SAM) is expected to intensify as a result of climate change (Rintoul, et al. 2018), bringing with it stronger winds, increased wind-energy input and a more intense mesoscale eddy field (Hogg et al. 2015). As the climate warms, we can anticipate an increase in heat input to the ocean and Antarctic ice-melt (both sea ice and ice shelves), ice sheet loss and changes to precipitation-evaporation patterns.

In the Southern Ocean, the addition of heat and freshwater will convert a larger volume of cold, upwelled deep water to lighter intermediate water, strengthening the upper cell of the overturning circulation. It is therefore expected that the tendency for delayed warming near Antarctica and enhanced ocean storage of heat and carbon further north will continue into the decades and centuries ahead.

Ocean research by the ESCC Hub has enabled the detection and attribution of climate changes and provides the robust science base from which mitigation and adaptation policies can be built that best meet the needs of Australia and the region. Tracking ocean change provides a powerful planetary thermometer and rain gauge and improved knowledge of drivers of Australian climate variability and climate extremes. Changes in the ocean circulation identified and explained by the ESCC Hub are used to understand the current and potential future evolution of ENSO, Indian Ocean Dipole (IOD) and SAM. This knowledge is the foundation that underpins ESCC Hub research, as well as national and international research, into climate impacts of drought, flood, bushfire, sea level inundation and other extreme climate events.

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