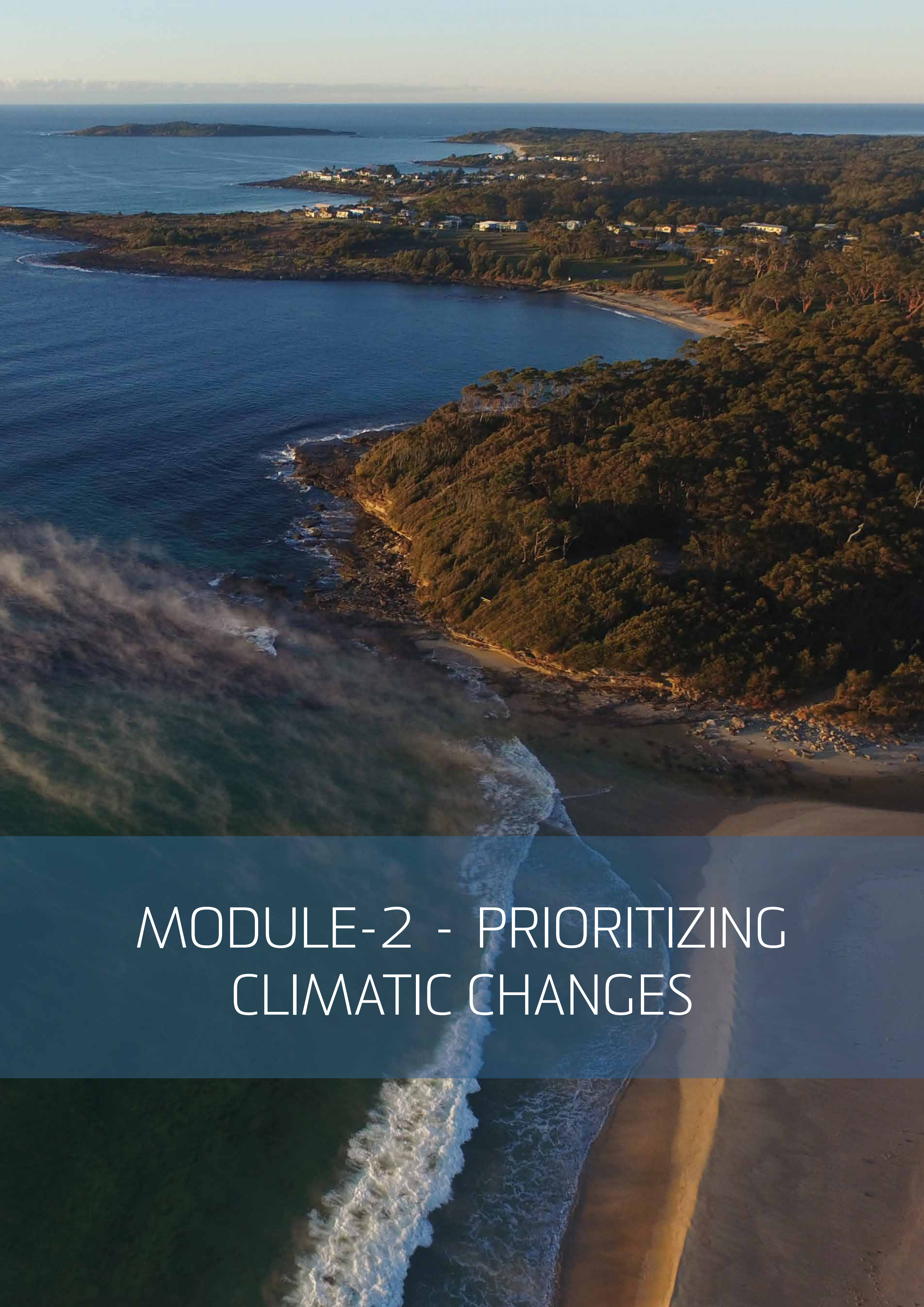

MODULE-2 - PRIORITIZING CLIMATIC CHANGES

“In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate.”
(IPCC Fifth Assessment Report)[1]

Green Point Creek, Pearl Beach, NSW [-33.545, 151.307] Photo: Chris Drummond, WRL, UNSW

MODULE OUTLINE

Preface

This Guide is the result of five years of research and close collaboration between project partners. The guidelines and information reproduced in this guide have been agreed by all project partners based on their extensive knowledge and experience in the field of estuaries and climate change with advice from the scientific community. The Guide has been published as a series of modules. Each module is a stand-alone document addressing an important aspect of assessing climate change risks in estuaries. The following modules are available in the series (titles are abbreviated here):

1. Introduction
2. **Changes in climate (this module)**
3. Changes in the physical environment
4. Changes in the ecology
5. Developmental stressors
6. Application of the framework
7. Review of ecological thresholds
8. Knowledge gaps and esearch needs

Summary of Module-2

The first step for assessing climate change in estuaries is to understand how the climate and ocean forcing (i.e. boundary conditions) of estuaries have changed and are likely going to change over the planning horizon. For the climate change risk assessment, it is critical to understand how projections for future climate are generated and how a range of hypothetical scenarios of human development and corresponding greenhouse gas emissions are used in these projections. This module provides a brief introduction to climate change science along with a guideline on how to quantify and prioritize changes in the climate and ocean system.

Questions addressed by Module-2

1. What is climate change and what are the main causes?
2. What are climate models and emission scenarios and how are they used to project the future climate?
3. How can changes in the climate drivers be prioritized for estuaries?
4. What are the key changes in climate faced by estuaries in New South Wales?

Cover photo

Entrance of Willinga Lake ICOLL during an opening, Bawley Point, NSW, Photo: Chris Drummond, WRL, UNSW.

This module should be referenced as

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Peer-review

Module-2 has been peer-reviewed by Dr. Nathan Waltham (TropWATER, James Cook University) and Dr. Melissa Wartman (Blue Carbon Lab, James Cook University).

Disclaimer

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Tip for readers

The modules in this series are designed to be read as double page booklets. To benefit from the many double page-sized figures and illustrations, it is recommended to read the modules in double page view, which is possible with most pdf readers. The first page is the booklet cover and should be in single page view.

1 What is climate change and what are the main causes?

Climate is commonly defined as the mean and variability of weather at a given location over a period of time ranging from months to thousands of years. Anthropogenic climate change is a long-term change (i.e. trend) in the climate system as influenced by humans. The changes observed over the last decades can confidently be attributed to human development-driven greenhouse gas emissions.[1]

> "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen."[1]

Figure 1 shows the observed globally-averaged atmospheric concentrations of the three most relevant greenhouse gases, CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide) obtained from ice core and atmospheric measurements since 1750. Higher concentrations of greenhouse gases in the atmosphere block more of the heat that the earth usually emits back into space, causing a warming of the earth surface, oceans and atmosphere. Notably, this heat-trapping or "global warming potential" effect is almost 300 times higher for nitrous oxide and around 25 times higher for methane as compared to the same mass of carbon dioxide.[2] This heat trapping effect has led to the addition of approximately 250 trillion Joules per second to the climate system in recent decades,[1] which is roughly equal to the energy released by four Hiroshima atomic bombs per second.[3]

As seen in Figure 2, the majority of this energy is stored in the upper 75 m of the oceans, with the atmosphere accounting for about 1% of the additional energy uptake.

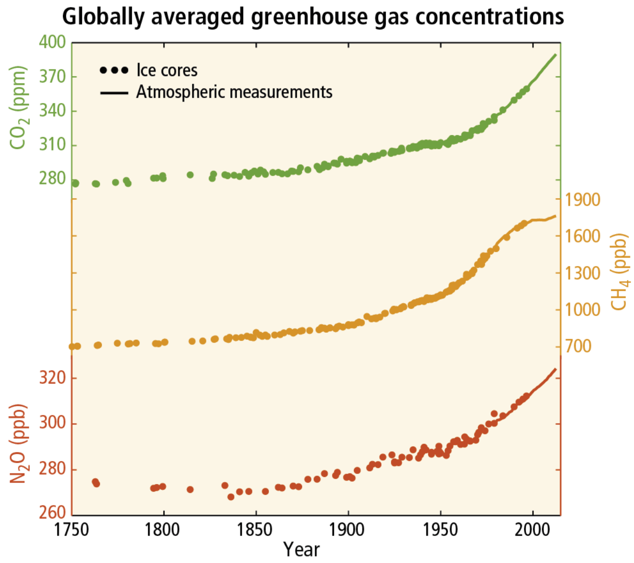


Fig. 1: Globally averaged greenhouse gas concentrations from atmospheric and ice core measurements. Source: IPCC Fifth Assessment Report, (Fig. 1.03-01)[1]

As a consequence, between 1971 and 2010, the upper 75 m of the global ocean warmed by around 0.11°C per decade. Notably, the term 'climate change' does not just refer to an increase in global temperatures but also includes changes in rainfall, sea levels, sea ice and wind patterns. Climate change can cause a change in the long-term averages as well as a change in the frequency and magnitude of extreme events. Trends in the global climate system are well established within the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC), stating that the warming of the climate is 'unequivocal'[1] (see Box-1).

The main purpose of this module is to provide guidance for assessing changes in climate relevant for estuaries based on suitable climate projections data. Many of the trends provided in this module are based on the best available datasets for NSW but climate science and models are constantly evolving and it is recommended to consider a range of different data sources. The following section provides a short summary of information sources on climate change in and around Australia that are recommended to be used in conjunction with this guide.

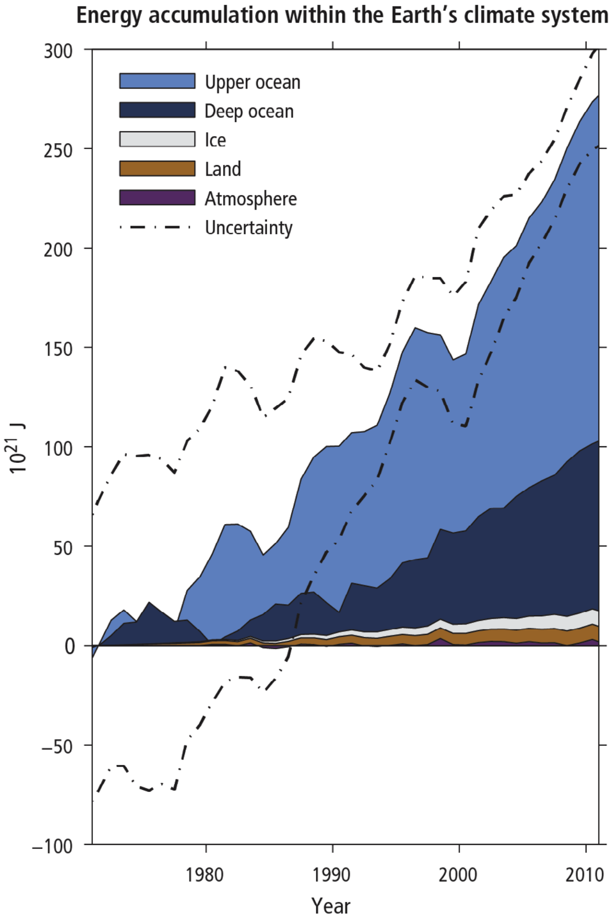


Fig. 2: Partitioning of the accumulation of energy in the Earth's climate system. Source: IPCC Fifth Assessment Report, (Fig. 1.02-01)[1]

1.1 Information and data sources

IPCC: The Intergovernmental Panel on Climate Change (IPCC) is an international consortium of experts established to provide objective assessments of the state of climate change and the underlying science. The IPCC assessment reports are the single most comprehensive evaluation of climate change and are subject to a rigorous peer-review process, which is why they are the most widely-used source of information for developing climate related policies by governments. The latest assessment report (5th) can be browsed or downloaded directly from the IPCC and represents an excellent resource for getting an overview of the current state of climate change and adaptation science.[A]

AdaptNSW provides high resolution climate projections along with a wide range of climate change and corresponding impact snapshots covering the entire state of NSW.[B] The high resolution climate projections were generated using an ensemble of state-of-the-art high resolution climate models over the NSW domain called NARCliM, which are presented in detail in this module and used extensively throughout the entire guide.

Climate Change in Australia: Another excellent resource for climate change science and projections for Australia is Climate Change in Australia, a large collaborative effort by the CSIRO and the Bureau of Meteorology.[C,4] Climate Change in Australia provides information, data and guidance for assessing and mitigating climate change impacts tailored specifically to the Australian region. The "Climate-Campus"[C] by Climate Change in Australia is a great resource for learning more about the global climate system and climate change in Australia.

Coast-Adapt is a information portal and decision support framework for assessing and mitigating climate change related risks specifically for Australia's coasts.[D] Coast-Adapt provides extensive information on the impacts of climate change and sea level rise on Australia's coasts along with a number of tools for assessing risks and developing mitigation strategies.

Further reading

A. IPCC fifth assessment report: http://ar5-syr.ipcc.ch
B. AdaptNSW: https://climatechange.environment.nsw.gov.au
C. Climate Change in Australia – Climate Campus: https://www.climatechangeinaustralia.gov.au/en/climate-campus
D. Coast Adapt: https://coastadapt.com.au/

2 What are climate models and emission scenarios and how are they used to project future climate?

The first section of this module provided an introduction to climate change, its drivers as well as appropriate sources of information and projection data. This section explains how projections of future climate are generated. Numerical models are the primary tools for assessing future changes in the climate system. These models simulate the evolution of the global climate system continuously for a range of plausible scenarios of greenhouse gas emissions and land use change. The outcomes of these future simulations are also referred to as projections of climate change. Climate projections are typically provided based on a set of representative scenarios of socio-economic development and greenhouse gas emissions.

These scenarios consider the range of possible trajectories in climate-relevant processes such as the adoption of emission policies (e.g. Paris Agreement) and renewable energy sources or changes in land use such as deforestation and agriculture. Each scenario is associated with different levels and trends of greenhouse gas and aerosol emissions, which can be translated into future concentrations of greenhouse gases in the atmosphere (i.e. the main driver of climate change). In their latest report (5th), the IPCC refers to these scenarios as Representative Concentration Pathways (RCPs).[1] RCPs are four scenarios that are named according to level of radiative forcing (i.e. their atmospheric heat trapping capacity) that they would lead to by 2100. These include a mitigation scenario leading to a low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6) and one high baseline greenhouse gas scenario (RCP8.5) (see Fig. 3).

RCP2.6 is a pathway that requires rapid development of technologies, population stabilisation and high GDP growth. Studies have shown that without immediate and significant development of negative emission technology, RCP 2.6 is unlikely to be reached. This means that using RCP2.6 projections for estuary management is likely to underestimate the impacts of climate change.[12]

RCP4.5 is based on an emissions target that is feasible with substantial changes in climate policy and emissions technologies stabilise emissions before 2100. It is not, therefore, a 'status quo' forcing pathway, it involves some change in human activity in the future. While it is feasible that this concentration pathway could occur, it would not be conservative approach to use RCP4.5 for estuary management. There are reasonable chances that the projections will underestimate realised climate change by the end of the century.[12]

RCP6 represents a scenario where climate policy and technologies stabilise emissions after 2100. It requires emissions technologies to be developed and global populations to stabilise around 2080. The 2100 greenhouse gas emissions are consistent with low – mid range estimates in literature of unabated emissions by the end of the century. RCP6 could be used for estuary management, as long as it is understood climate drivers could vary more than what is predicted by the models.[12]

RCP8.5 assumes fast population growth, slow development of abatement technologies and slow GDP growth. It is a baseline scenario that sets the target radiative forcing levels to the high range estimates of unabated emissions with little change in climate policy or technology. It will give the most conservative estimates to be used for estuary management.[12]

Fig. 3: Summary of the four representative concentration pathways used in the fifth IPCC assessment report.[1]

In the previous IPCC assessment report (4th), a slightly different set of future scenarios were used instead of the RCPs, which are commonly referred to as SRES scenarios.[5] The projected CO_2 emissions and resulting atmospheric CO_2 concentrations corresponding to the four RCP scenarios is shown in Fig. 4. All scenarios apart from RCP8.5 require the annual amount of CO_2 released into the atmosphere to be reduced at some stage. After two years of stabilising, emissions released from fossil fuels burning and other sources have reached a new record high of 10±0.5 gigatons of carbon (GtC) in 2017. A good overview of global carbon emissions along with historic and future trajectories is provided by the *Global Carbon Budget*.[A]

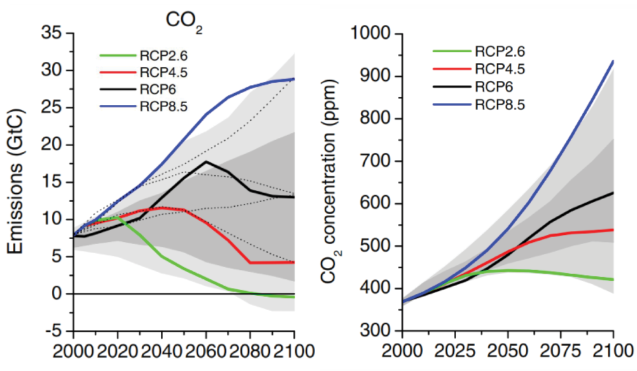


Fig. 4: CO_2 emissions and corresponding atmospheric CO_2 concentrations for the four IPCC representative concentration pathways[12] (GtC = Gigatons of carbon)

Figure 5 illustrates the complexity involved with determining future concentration of greenhouse gases in the atmosphere based on emission scenarios. CO_2 is released through burning of fossil fuels and industry as well as through Land-use changes such as deforestation. At the same time, parts of the atmospheric CO_2 are absorbed by the oceans (causing oceanic acidification) and back into the land cover (i.e. forests and plants). As seen in Box-1, changes in the climate and ocean system projected for the end of the century vary drastically across the four RCPs. Global mean temperature, for instance, is expected to increase by 4°C by the end of this century for the RCP8.5 scenario but likely to stabilize at around 1°C increase for RCP2.6, compared to the baseline average temperature from 1986-2005.[1] The large amount of additional energy contained in the earth system corresponding to the already observed increase in average land and ocean surface temperature of around 0.78°C (2003-2012 compared to 1850-1900) was shown in Figure 2.

Choosing the RCP for estuary management is ultimately up to policymakers to decide. However, it is important that the users of the information understand the implications of this choice.

It is critical that estuarine managers and coastal communities have a good understanding of emission scenarios and the consequences of choosing a specific scenario as the basis for the climate change risk assessment. Notably, some climate change processes such as sea level rise have very slow response times so that even in the face of immediate actions associated with RCP2.6, sea levels will continue to rise throughout the century (see Fig. 6 in Box-1).

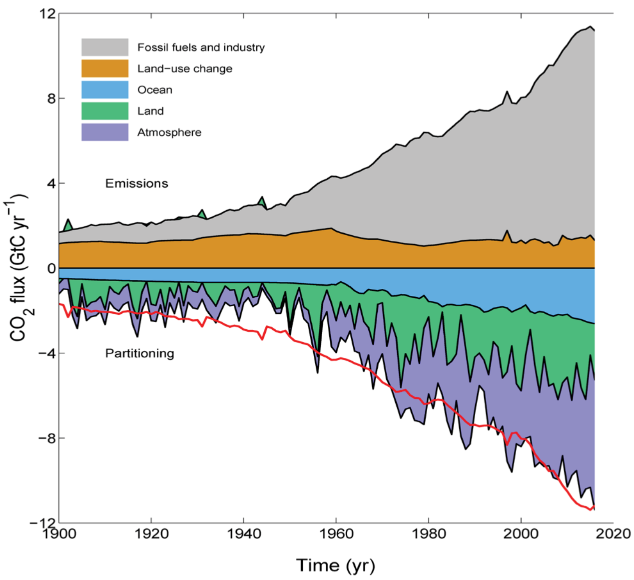


Fig. 5: Historic carbon emissions and absorption rates partitioned by major components of the Earth's climate system[E]

Box-1: IPCC & major global climate trends and projections

The IPCC assessment reports are the single most comprehensive analyses of climate change and the underlying science. Due to its intergovernmental nature and comprehensiveness, the data and projections provided in the assessment reports are widely-used as the basis for climate related policies by governments and managers around the world.[1] Each assessment report is comprised of three volumes, which present the results of each working group and a synthesis report, which provides a summary specifically for policy makers.[1] While not providing any political opinion or suggestions for policy making, the IPCC reports draw a clear picture: Climate change is already occurring; it is largely attributable to human greenhouse gas emissions and is causing increasing negative impacts on humans and ecosystems.[1] The dramatic historic and future changes to the earth system are shown below, where RCP2.6 is the lowest and RCP8.5 the highest emission scenario. For RCP8.5, global temperature increases of up to 5.5°C, sea level rise of up to 95 cm and a drop in global average surface ocean pH below 7.8 are possible by 2100.

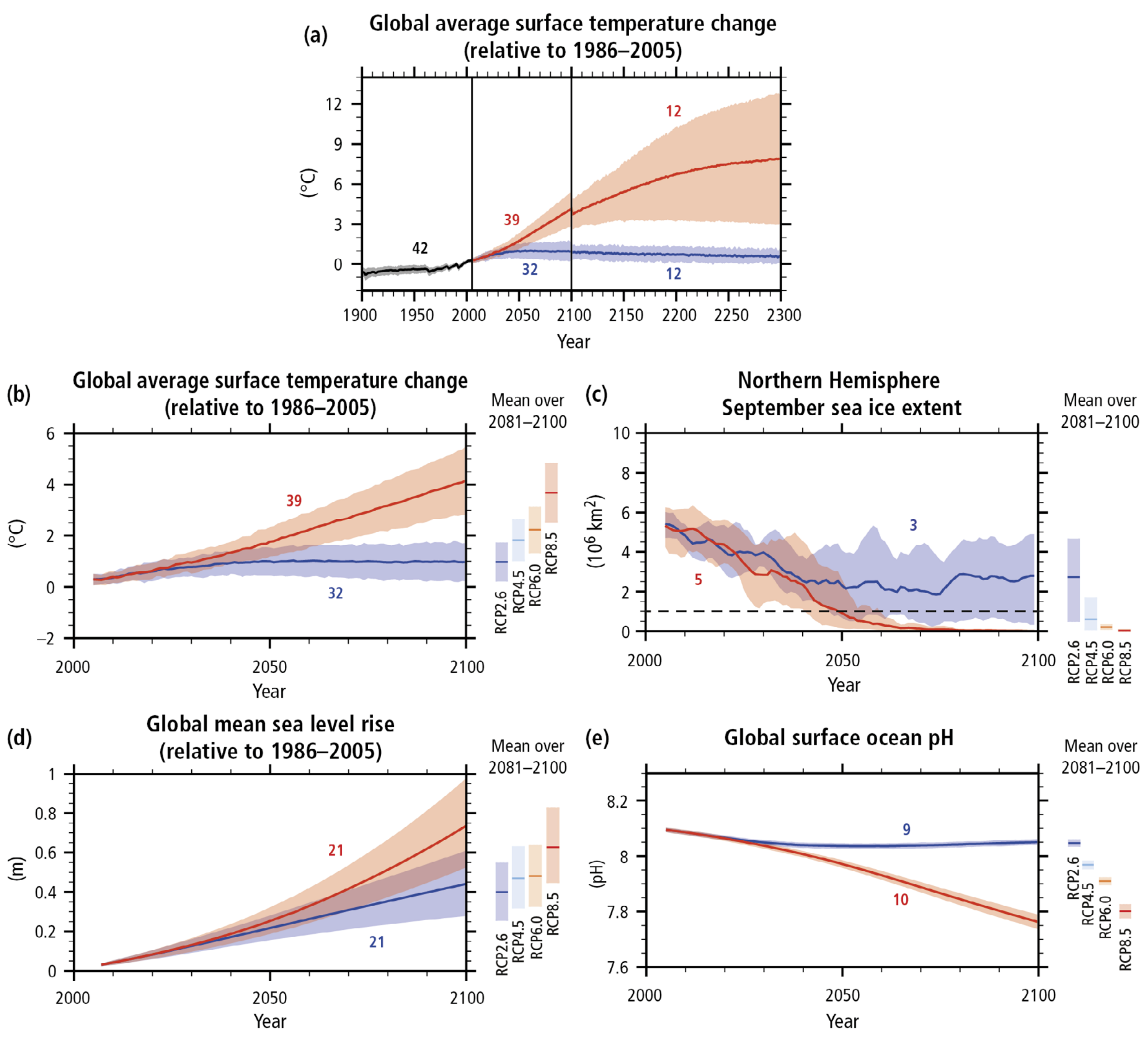


Fig. 6: Globally averaged changes in surface temperature, northern hemisphere sea ice extent, mean sea level and ocean pH relative to the 1986-2005 baseline period. For all panels, time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The number of CMIP5 models used to calculate the multi-model mean is indicated. The mean and associated uncertainties averaged over the 2081–2100 period are given for all RCP scenarios as coloured vertical bars on the right hand side of panels (b) to (e). For sea-ice extent (c), the projected mean and uncertainty (minimum– maximum range) is only given for the subset of models that most closely reproduce the climatological mean state and the 1979–2012 trend in the Arctic sea ice. (IPCC 5th assessment report Fig 2.1-01)[1]

"Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks." (IPCC Fifth Assessment Report)[1]

Drone view of a rocky shoreline, Sydney, NSW; Photo: Chris Drummond, WRL, UNSW

2.1 Global climate models

Global climate models (GCMs), also known as global circulation models, have been developed by scientists across the world to physically model the global climate system. They are mathematical representations of all the processes occurring in the atmosphere, the land surface, the oceans and the cryosphere (ice) as well as the interactions occurring between those systems. Earth system models are extensions of GCMs that in addition to all physical processes, also model biogeochemical cycles (i.e. carbon fluxes) and hence, can account for feedbacks between climate and major ecosystems.[F] GCMs are used both for short-term and seasonal weather forecasting as well as for projecting (from now into the next few centuries) how the climate system will respond to atmospheric greenhouse gas concentrations prescribed by the emission scenarios (i.e. RCPs). Developing and maintaining accurate GCMs requires extensive human and computational resources and they are typically hosted by large research centres and the Bureau of Meteorology, the CSIRO and a consortium of universities together are maintaining a GCM, the Australian Community Climate and Earth System Simulator (ACCESS).

No model is perfect, and this applies to global climate models as well. GCMs differ in horizontal and vertical resolution, the way they solve numerical equations and how they represent processes that occur at scales that are far smaller than the model grid cells (parameterizations). The comparison of modelled output with historical observations of the climate system show that there is no "best" model and each GCM has unique strengths and weaknesses. Consequently, all GCMs have areas for which they predict slightly hotter or wetter conditions compared to the observed climate. These comparisons also show that considering multiple models (i.e., an ensemble of models) tends to reduce these errors. In addition, the use of an ensemble of models, assuming all models are equally plausible, allows quantification of uncertainty in the future projections. As such, the spread of the projections within the ensemble can be used as a measure of the confidence with a small spread (i.e. good agreement between models) indicating high confidence.

The climate projections in the IPCC reports are an ensemble of GCMs that are organized under the Coupled Model Intercomparison Project (CMIP), with CMIP-5 forming the basis for the fifth IPCC assessment report.[1]

> The use of an ensemble of global climate models for projecting future climate states is comparable to reading multiple independent newspapers and magazines to form an objective opinion about a certain matter, rather than relying on a single information source.

Each GCM is used to simulate the foreseeable future using the same four RCPs as forcing. The idea behind CMIP-5 is that despite limitations of individual models, the group or “ensemble” of models will provide a sufficiently wide range of plausible climate futures. For instance, one of the models might project a substantial increase in annual rainfall for a given region by 2050 for the RCP6 scenario whereas another one might project a decrease for the same scenario. The median of the projected change in annual rainfall of all 50 models might be around 0 mm. From a planning perspective, this ensemble of projections can be interpreted such that increases and decreases in total annual rainfall are possible, while no change is the most likely outcome for the RCP6 scenario. If the majority of models project an increase in annual average temperature of 0.5±0.05°C by 2050 for RCP6, then this projection can be interpreted as robust or simply put: It is likely that RCP6 will lead to this increase in temperature by 2050. The use of an ensemble of climate models for prioritizing climate change processes based on their relevance for estuaries is illustrated in detail in Box-2.

2.2 Regional climate models

Despite the steady increase in supercomputing power in the last decades, the horizontal and vertical resolution of GCMs is quite limited and they do not provide climate information that is suitable for assessing climate change impacts at the local estuary level. In addition, they are usually tuned to best represent global scale climate processes, rather than to best match local scale weather patterns.[F] From an estuary management perspective, the regional climatology (i.e. coastal wind fields) and hydrology (i.e. catchment rainfall and runoff) are highly relevant and GCMs can typically not resolve those processes with enough detail for use in adaptation planning. To overcome this limitation, GCM projections can be "downscaled", either using statistical or dynamical methods, into specific smaller regions. Regional Climate Models (RCMs) are numerical models that simulate climate processes at much higher resolution than GCMs typically over a limited area of the globe (Figure 7). In dynamical downscaling, the resolution of GCM climate change projections is increased by running a high-resolution physical climate model with the GCM outputs as boundary conditions.[6] Using the GCM projections as a boundary ensures that the finer scale simulations are still consistent with changes in the global climate system, while the higher resolution allows for capturing local effects of topography and other land surface features.

> The spread of the projections amongst the model ensemble members can be used as an indicator of the robustness of the projection.

2.3 NARCliM

In order to provide state-of-the art and locally relevant climate projections for adaptation and impact planning, the NSW and ACT Governments launched the NSW and ACT Regional Climate Modelling (NARCliM) Project. NARCliM is a 12-member ensemble that provides high resolution climate projections for the wider NSW domain and medium resolution projections for the Australasian domain (Figure 8). NARCliM uses three different configurations of the Weather Research and Forecasting RCM to dynamically downscale four GCMs under the A2 emission scenario. The CMIP-3 models formed the basis of the fourth IPCC assessment report and were released in 2010.[7] The A2 emission scenario[5] is comparable to the high-emission RCP8.5 scenario. Although the CMIP-5 GCM ensemble is considered more advanced than the CMIP-3 ensemble, the IPCC fifth assessment report concluded that there is good agreement between CMIP-3 and CMIP-5 projections for large scale patterns and the magnitude of climate change.[8]

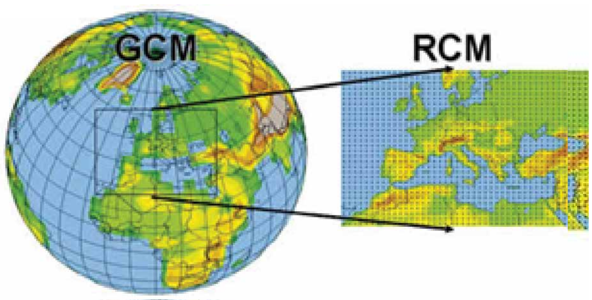


Fig. 7: Illustration of the difference in resolution between regional (RCM) and global (GCM) climate models and the nesting of RCMs in GCMs. Source: WMO[11]

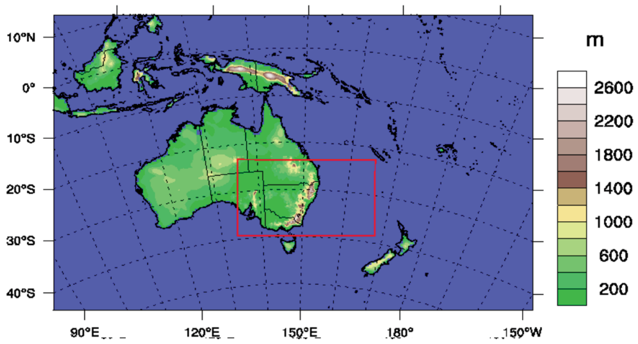


Fig. 8: Map illustrating the 10km (red rectangle) and 50km resolution (full map extent) NARCliM model domain[9]

The 12 models used in NARCliM were chosen to maximise the information content of the ensemble (by considering independence of GCMs) as well as spanning the plausible future climate changes present in the full CMIP-3 ensemble.[6] When considering changes in temperature and rainfall, the 12 models provide a representative picture, indicating both increases and decreases in mean precipitation as well as temperature increases between 1.6 and 2.6°C. NARCliM is the primary resource used for projecting future climate states in this guide. NARCliM doesn't provide projections for ocean variables such as sea surface temperature and oceanic acidity and therefore, CMIP-3 and CMIP-5 GCM data are used for all ocean variables instead.

Further reading

E. Global Carbon Project (2017) Carbon budget and trends 2017. [www.globalcarbonproject.org/-carbonbudget]

F. Asch, R. G., Pilcher, D. J., Rivero-Calle, S., & M. Holding, J. (2016). Demystifying Models: Answers to Ten Common Questions That Ecologists Have About Earth System Models. Limnology and Oceanography Bulletin, 65–70.

3 Prioritizing changes in climate drivers that are relevant for estuaries

The previous section introduced how climate change projections are generated by ensembles of GCMs and RCMs and how the likely magnitude of changes depends on the emission scenario applied to the models. This section illustrates how climate model projections can be used to objectively quantify and prioritize changes in climate and ocean variables that are relevant for estuaries.

Climate models are complex and provide outputs for a very large number of climate and ocean variables. When an ensemble of GCMs is used to make global projections of future climate for multiple emission scenarios, very large datasets are created. Analysing these datasets for trends in average and extreme conditions typically requires expert knowledge and access to high performance computing platforms. For climate change impact assessment, the full datasets are often not required and subsets in space and time of key climate variables are typically sufficient.

Both Climate Change in Australia and AdaptNSW provide user friendly datasets that are derived from large GCM and RCM ensembles. These datasets can be projected time series (i.e. daily or hourly) of key variables at a specific location or a statistical summary of projected changes for future periods averaged over broad climatic regions. For climate change impact planning, it is practical to use a limited number of equally-long periods such as the present-day (1990-2009), near-future (2020-2039) and far-future (2060-2079) periods adopted by the NARCliM ensemble. The NARCliM ensemble currently provides the most fine-scaled and locally-relevant climate projections available for NSW. Box-2A and 2B provide a step-by-step illustration of how future changes in averages and extremes can be generated from the NARCliM ensemble projection data.

Narrabeen Lagoon – ICOLL – [-33.702, 151.306]

Understanding natural climate variability, ensemble projections and extreme indices is critical for assessing climate change in estuaries. These concepts are used extensively in the remaining chapters.

These boxes also illustrate how to prioritize these changes based on their significance for estuaries. This is done by comparing the projected changes with the historic (i.e. natural) intra- and interannual variability that is experienced by the local system. For instance, the total annual rainfall in NSW is known to vary drastically from one year to another and can be anything from under 500 mm to more than 1500 mm. In the face of this very high level of natural interannual variability, a projected increase of e.g. 20 mm in total annual rainfall in an estuarine catchment can be considered as insignificant.

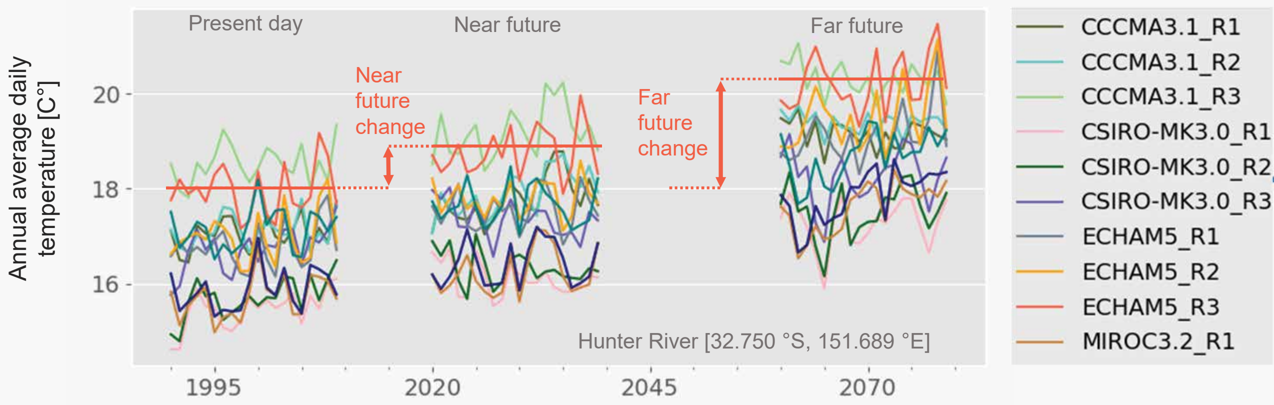
A variety of observational and modeled climate datasets are used in the remainder of this chapter. Climate projections are based on the NARCliM ensemble model if possible and on Climate Change in Australia ensemble summaries for all remaining variables (mainly ocean variables). Observed data for the majority of variables is extracted from SILO gridded climate datasets for Australia, which are generated based on interpolation of available weather station data (https://silo.longpaddock.qld.gov.au/gridded-data). The six estuary sites along the NSW coast listed below are used to illustrate relevant climatic changes. Climate projection data is extracted for the coordinates shown in square brackets.

- Richmond River [28.950°S, 153.294°E]
- Lake Cathie [31.516°S, 152.814°E]
- Hunter River [32.750°S, 151.689°E]
- Georges River [33.984°S, 151.012°E]
- Shoalhaven River [34.865°S, 150.544°E]
- Nadgee Lagoon [37.423°S, 149.863°E]

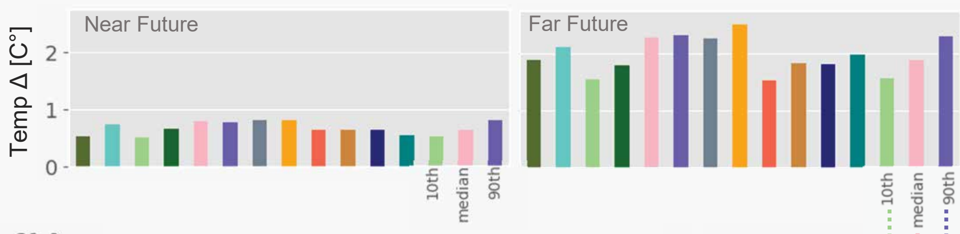
Box-2A: Prioritizing climate change using NARCliM

Quantifying future changes using the NARCliM ensemble

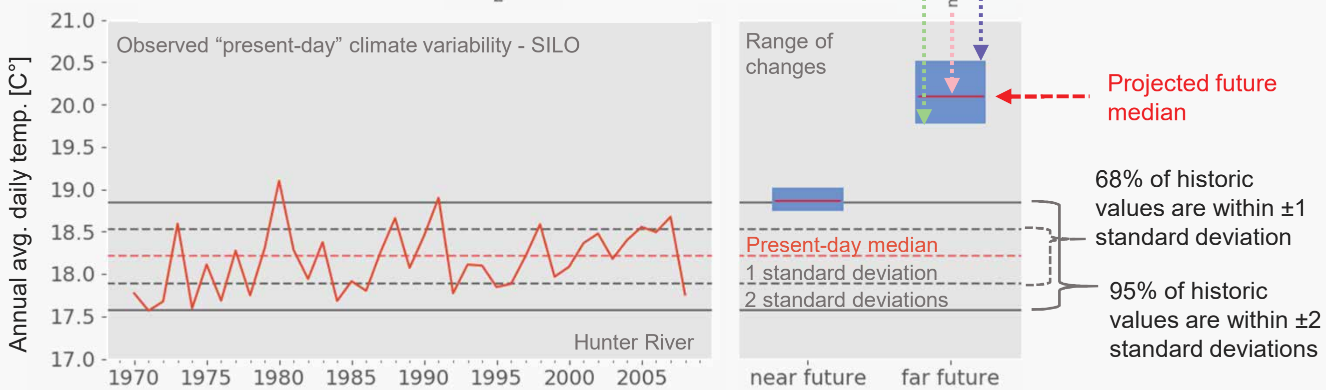
NARCliM is a suit of 12 models consisting of 4 GCMs, each dynamically downscaled using the WRF regional climate model under 3 different configurations, hereafter stated as R1, R2 and R3. Each color in the following graph corresponds to one of the 12 models in the ensemble. Box 2-2A and 2-2B use NARCliM data extracted over the Hunter River estuary 32.750°S, 151.689°E unless otherwise specified.



The spread in the model outputs for present day conditions is due to the unique bias of each model, which is a consistent over or under estimation. It can be assumed that this bias is consistent through time, which allows us to use the differences between the averages of the present-day (1990-2009), near (2020-2039) and far future (2060-2079) as a measure of future change. For each model in the ensemble, this approach yields a change for the near and the far future. To summarize the changes projected by the NARCliM ensemble, we calculate the median, 10th and 90th percentile of all changes.



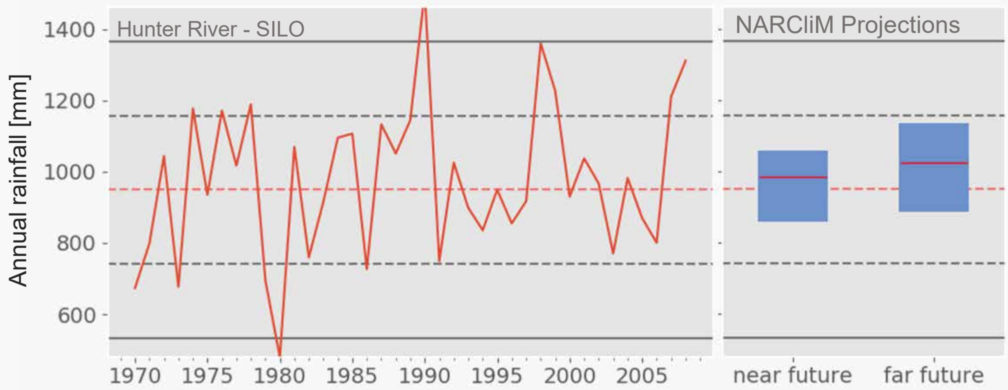
Adding the range of ensemble changes to present day averages, illustrates i) the magnitude of likely changes and ii) how well the models agree.



Delta change plots: *Ecosystems are adapted to a certain level of natural inter and intra-annual variability. Significant impacts occur when climate processes increasingly reach states outside of historical variability (see Module 1). Here, we use the median ± 1 & 2 standard deviations as a measure of natural variability. The projected changes in the mean are added to the historic median to be compared against the upper and lower boundaries of natural variability. These delta plots are used in the remainder of this module.*

Changes in average climate conditions

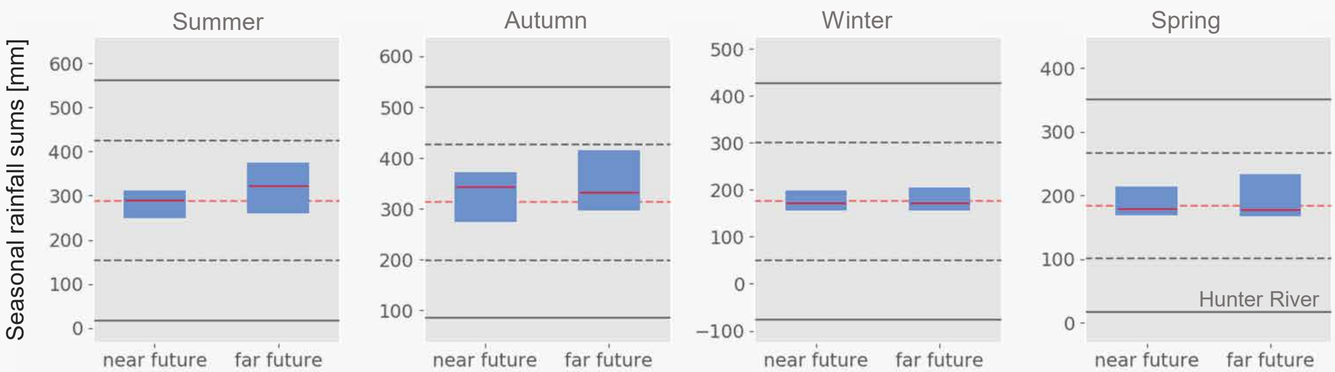
Increasing temperature is considered the most direct manifestation of climate change and the change plot on the previous page illustrates the undeniably significant temperature increases projected by NARCliM. Not all climate variables undergo such obvious changes and rainfall is a good example. The graph below shows the range of NARCliM ensemble changes of annual rainfall sums in parallel to the historic time series.



When looking at changes in annual or seasonal rainfall sums, limited change is noticeable and even the most extreme projections appear insignificant when compared with historic interannual variability.

Changes in seasonality

The plot above shows that there will be a limited shift in annual rainfall totals in the future but does this mean that rainfall isn't changing? Research shows that rainfall is changing in several ways and hence, the above method alone is not sufficient to complete a first pass assessment on the projected changes. In addition to shifts in average conditions, it is necessary to also look at shifts in seasonality and the magnitude and frequency of extreme conditions. The graphs below indicate the shifts in seasonal rainfall sums for the near and far future as projected by NARCliM.



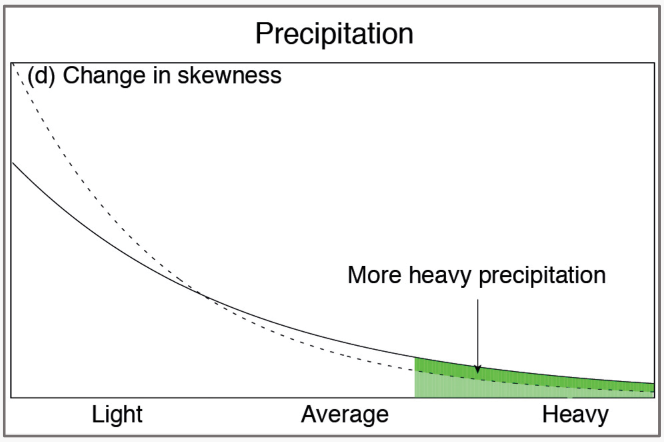
While limited change is indicated in seasonal rainfall sums (when compared with the very high level of present-day interannual variability) it appears that summer and autumn rainfalls are more likely to increase, whereas winter and spring rains might decrease. While the projected changes in average annual rainfall sums appear insignificant (Box 2-2A), changes in the frequency and intensity of extreme rainfalls could be entirely masked out in this approach. Box 2-2B illustrates how potential changes in the extremes can be quantified using extreme indices.

See Box 2-B

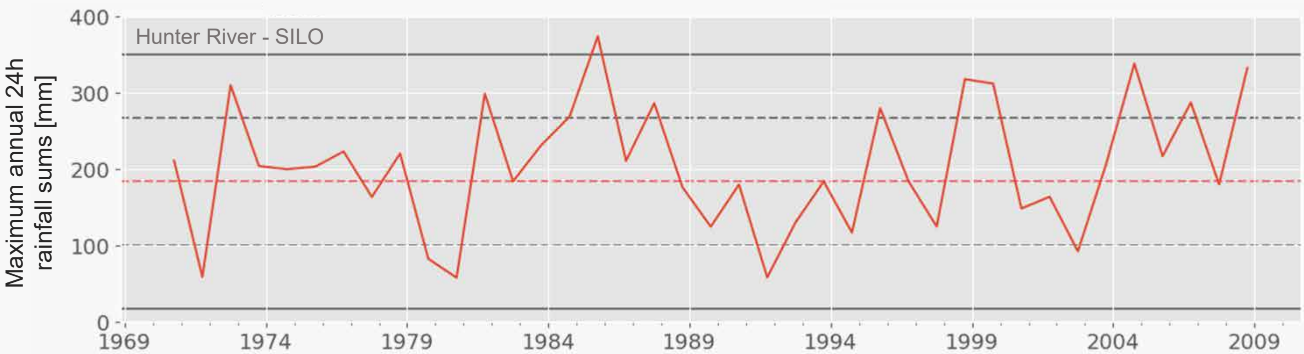
Box-2B: Prioritizing climate change using NARCliM

Changes in rainfall extremes

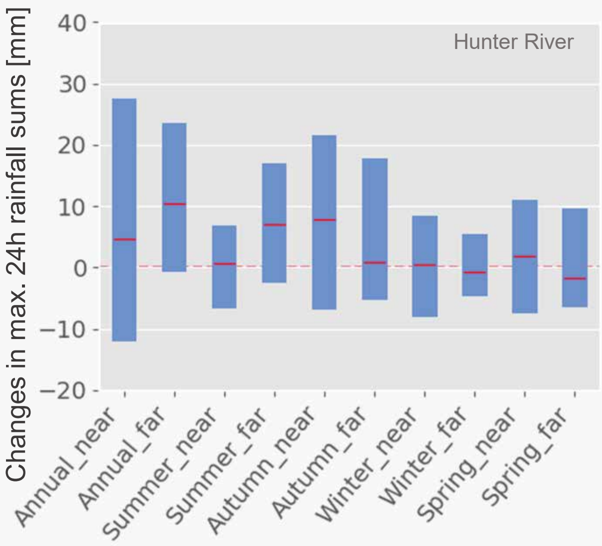
The figure to the right shows the distribution of all rainfall across different intensities with a warming climate typically causing more rainfall at heavy intensities and less rainfall at light intensities, with the total annual sums possibly unchanged. To quantify these changes, long-term averages or sums are not suitable and extreme indices are a more appropriate tool. The *Expert Team on Climate Change Detection and Indices* has developed a list of 27 extreme indices that are commonly used to quantify climate extremes.



Shifts in rainfall extremes. Source: IPCC AR4[2]



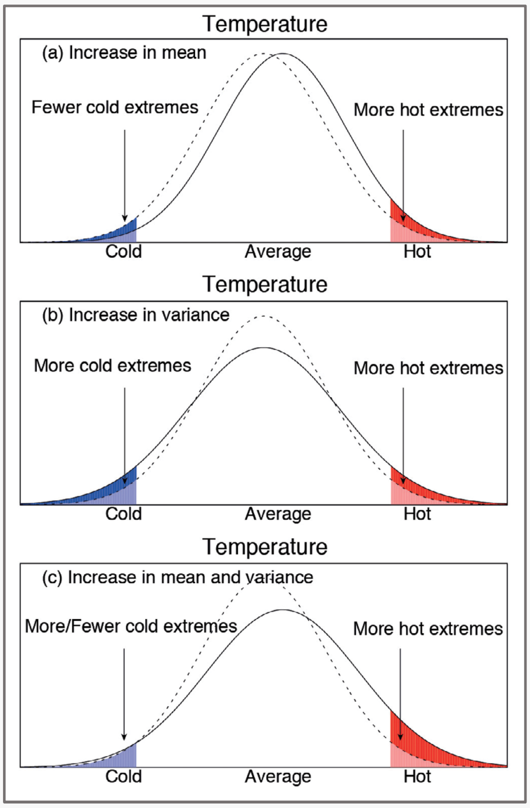
Maximum 24-h rainfall: A simple example of an extreme index is the maximum 24-h rainfall sum (24h-max) for a given time period (i.e. monthly, seasonal or annual). The annual 24h-max rainfall for a recent historic time period over the Hunter River Estuary is shown above. Similar to annual rainfall sums, there is a high level of interannual variability in the 24h-max rainfall, with a historic median of 190 mm 24h^{-1}.



Changes in extremes: Since very high 24h-max rainfalls are associated with large floods, changes in this index are highly relevant for estuaries. To quantify these changes, we can apply the change method presented in Box 2-A, which is directly applicable to extreme indices. We can see that for the 24h-max rainfall, the models do not agree well on the projected changes, with some indicating increases and others decreases at both the annual and seasonal level. For instance, projections for the near future annual 24h-max rainfall range from increases of more than 25mm to decreases of more than 10mm, illustrating the uncertainties involved. Considering the whole ensemble, however, average increases of over 20 mm in 24h-max rainfall are possible for the near and far future. See Box-2A (bottom left) for an explanation of the plot.

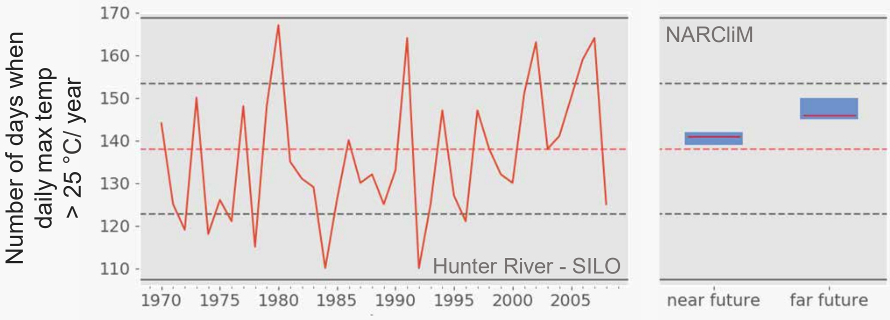
Changes in temperature extremes

Any assessment of the significance of projected changes needs to account for changes in average as well as extreme conditions, with the latter requiring the analysis of extreme indices that are of particular relevance for estuaries. Similar to rainfall, there may be changes in the duration and intensity of extreme events such as heatwaves. The figure to the right illustrates the difference between changes in the mean (a) vs. the variance (b) of temperature as well as a combination of both changes (c). In scenario (a), the entire distribution is shifted towards higher temperatures, causing an increase in the mean temperature, maximum temperature and the number of very hot days. In scenario (b), an increase in both hot and cold extremes in response to climate change does not lead to a change in the mean temperature since both changes are averaged out in the calculation of the mean. Scenario (c) is likely the most common with climate change altering both the mean and variance of climate variables in some form. Considering the eco-hydrological system of estuaries as a whole, both changes in average climate conditions as well as the occurrence and intensity of extreme weather are important.

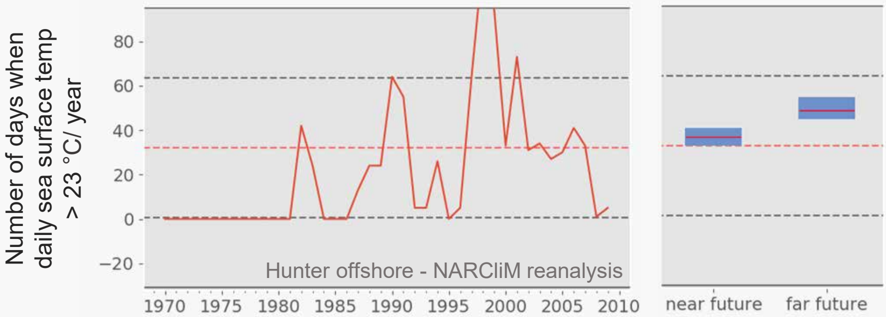


Shifts in temperature extremes. IPCC AR4[2]

Example temperature extreme indices



Number of summer days: Annual count of days when daily maximum temperature > 25°C. The number of summer days is highly variable in the Hunter (between 110 and 170 days) and NARCliM indicates that it might increase by up to 7 days in the far future.



Number of warm water days. A simple "days > threshold" index can be directly applied to sea surface temperature (SST). The number of days where the ocean temperature exceeds 23°C could increase by around 16 days (median of ensemble change) per year in the far future.

4 What are the key changes faced by NSW estuaries?

When performing a climate change risk assessments or adaptation study, it is critical to understand how both average and extreme weather conditions have already changed and are expected to change over the course of this century. This section provides an illustrative summary of observed recent historic and likely future changes in climate and ocean variables that are relevant for estuaries, namely air and ocean temperatures, rainfall, wind, sea levels and oceanic acidity.

4.1 Air Temperature

Changes in averages: Increasing temperature is considered to be the most reliable indicator of climate change and the confidence of future projections is high. Independent of the type of model used (i.e. GCM vs. RCM), all state-of-the-art model ensembles project a warmer future climate for Australia accompanied by more frequent, hotter and longer heatwaves.[14] When looking at annual average temperatures at the example estuary sites, the NARCliM projections point towards increases of around 0.6°C and 1.9°C for the near and far future respectively and these increases are relatively consistent along the NSW coast (Figure 9). It is also important to consider that the average temperature over the Australian continent has already warmed by about 0.9°C since 1950.[14]

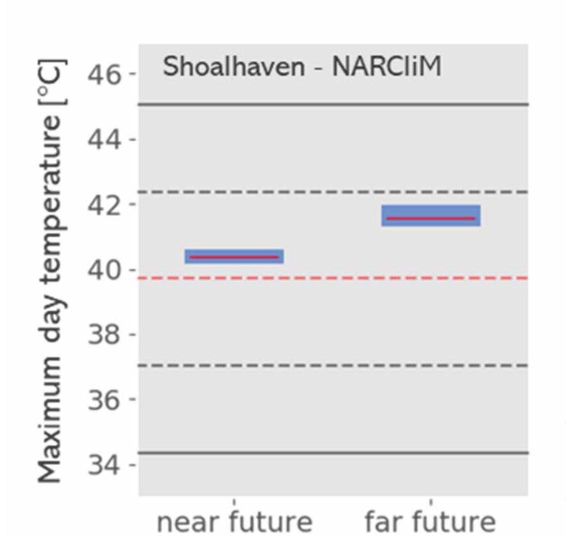


Fig. 10: NARCliM projections of changes in annual maximum day temperature relative to the 1990-2009 baseline for the Shoalhaven Region. Present day variability (horizontal lines representing median ±1 & 2 standard deviations) is based on SILO data.

Changes in extremes: As illustrated in Box 2, changes in average conditions are sometimes accompanied by changes in the extreme states such as extreme hot days and heatwaves. One extreme metric is the maximum temperature observed in a given year. Figure 10 shows that increases of close to 2°C are projected for the Shoalhaven River for the peak temperature.

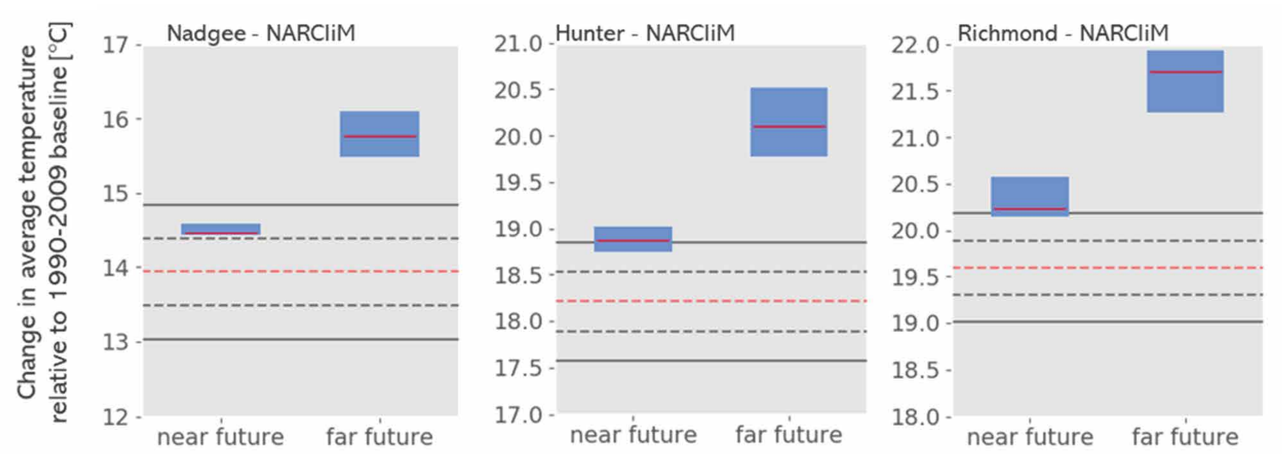


Fig. 9: Projected changes in the average annual temperature relative to the 1990-2009 baseline for the Nadgee, Hunter and Richmond region. Present day variability (horizontal lines representing median ±1 & 2 standard deviations) is based on SILO data.

> "A heatwave is when maximum and minimum temperatures remain unusually high for several days."[15]

In addition to the maximum observed temperature, the intensity, duration and number of heatwaves is of very high relevance for ecosystems. Heatwaves are known to be the deadliest of all extremes in Australia since they cause the most fatalities and they can also have devastating impacts to natural systems.[14] Although several metrics exist for defining heatwaves, they are typically considered periods of consecutive days with "hotter than usual" temperatures. In Sydney, heatwaves already start 19 days earlier now (1981- 2011) than in the 1950-1980 baseline period.[16]

The number (per year), duration and intensity of heatwaves along the NSW coastal fringe are all projected to increase in the future.[15]

4.2 Water Temperature

Changes in averages: Changes in ocean temperature directly manifest in changes in estuarine temperatures and the Tasman Sea is regarded as one of the fastest warming oceans globally.[14] Sea surface temperatures (SST) in the Tasman Sea off the NSW central coast have already warmed by approximately 1.44°C between 1950 and 2010 at a rate of 0.024°C/year (Figure 11). This warming trend is likely to continue and projections for the near and far future point towards further increases of 0.4-1.0°C by 2030 and around 2-4 °C respectively for the RCP8.5 scenario.[33]

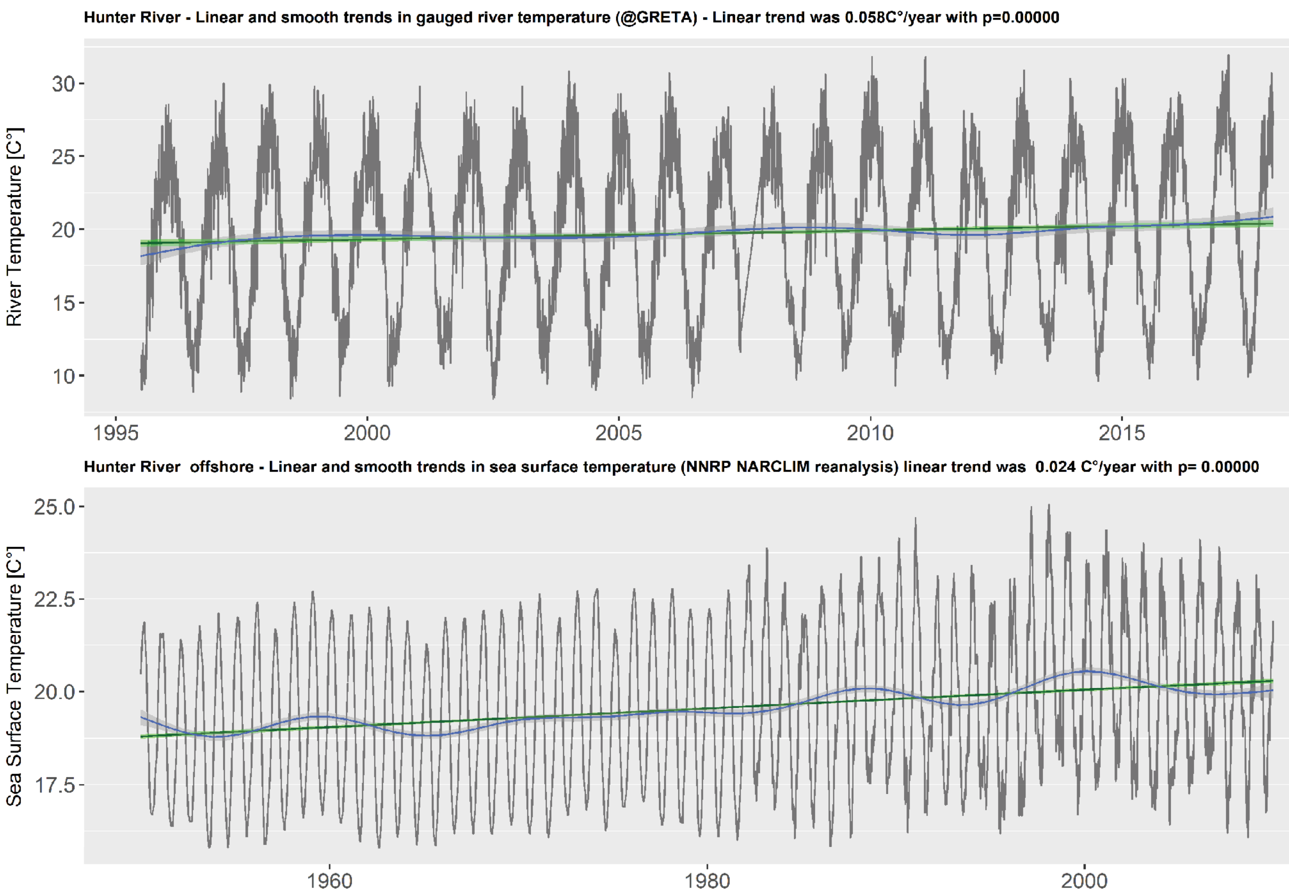


Fig. 11: Observed linear and non-linear trends in river (Hunter River near Greta, NSW) and sea surface temperature for the Hunter River estuary. Non-linear trends are generated using the GAM data smoothing technique[20]. Source of river temperature data: NSW Department of Primary Industries. Source of sea surface temperature data: NCEP/NCAR reanalysis[40]

In NSW, the ocean temperature is controlled by the East Australian Current that transports the warm tropical waters off northern Queensland southward towards NSW and Tasmania. This current has been advancing south about 350 km over the past 60 years[1] and is accelerating the warming of the ocean along the NSW and Tasmanian coast, with 2016 being one of the warmest years on record (Figure 12).

Changes in extremes: The steady increase in average SST leads to more intense and frequent marine heatwaves, as it increases the probability of large heat anomalies.[22] Marine heatwaves are unusually high SSTs that typically last for several days and are driven by atmospheric and oceanographic processes. These extreme states can have direct and lasting impacts on marine ecosystems. A recent example of an extreme marine heatwave took place in 2011 off the coast of Western Australia. This marine heatwave caused substantial ecological impacts including a reduction in seagrass abundance and increases in tropical fish species.[18]

Another recent example is the 2016 Tasmanian marine heatwave, during which water temperatures remained well above the long-term average for more than three consecutive months (Figure 12). Several marine heatwave indices have been developed for quantifying temperature stress on marine ecosystems, including a recent index that uses an approach that is comparable to the more studied atmospheric heatwaves.[27] Depending on the specific heat related vulnerability of particular ecosystem components, these indices can either be a simple maximum temperature exceedance or an integration of temperature stress over a defined period of time.

In Box 2-B, it was shown that the number of days per year where SST is expected to exceed 23°C is projected to increase by up to 16 days (median) in the far future for the Hunter offshore location. Figure 13 shows the projected increases in the annual maximum daily SST compared to the historic variability (projections are based on the four GCMs that are used as forcing in NARCliM).

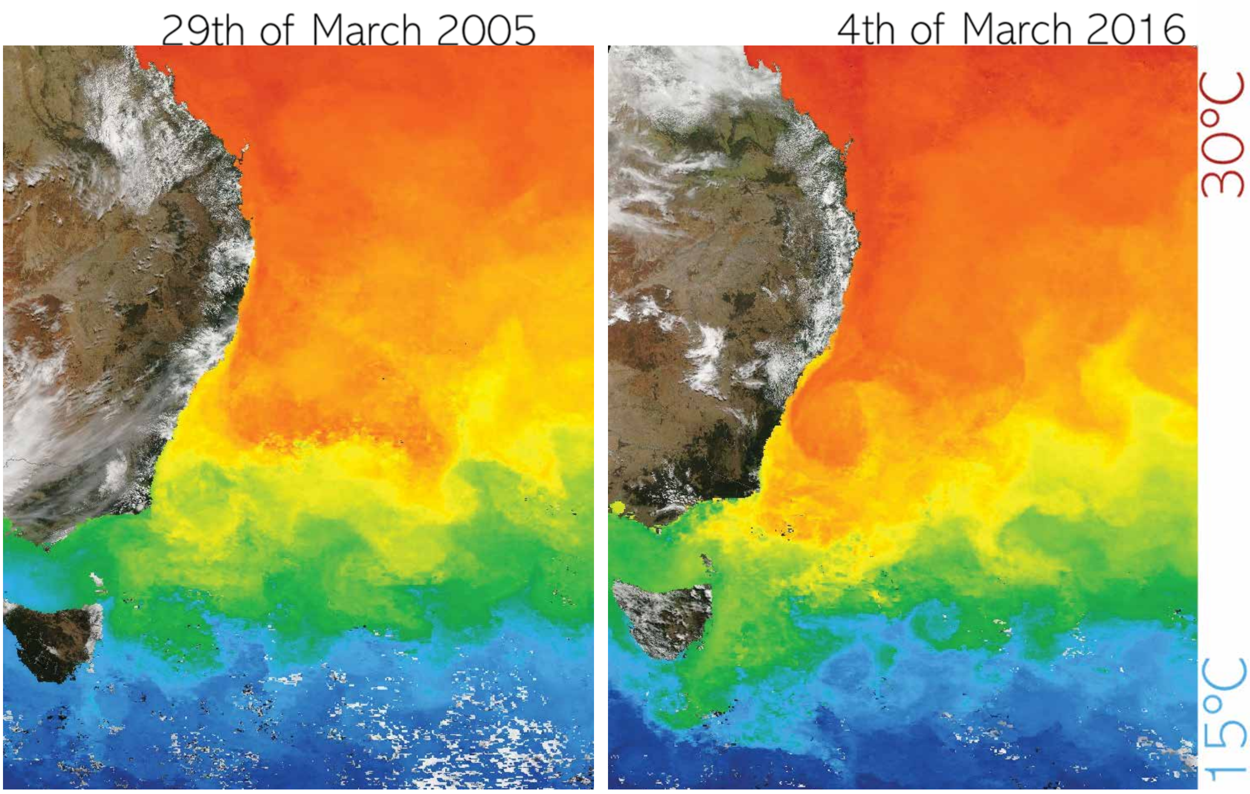


Fig. 12: MODIS satellite sea surface temperatures during the 2016 Tasmanian marine heatwave compared to 2010 temperatures for the same month. Data source: NASA Worldview

These projections highlight the extreme temperature states that are likely to be faced by NSW coastal ecosystems in the foreseeable future. While marine heatwave indices are suitable tools for quantifying extreme offshore temperature states, they are not directly representative of estuarine temperatures. Estuaries experience impacts from both terrestrial and maritime heatwaves but the response to these impacts is complex and unique for each estuary. Ultimately, it is necessary to define a third type of heatwave, the *'Estuarine Heatwave'*.

> In addition to atmospheric and marine heatwaves, it is necessary to define a third type of heatwave, the 'Estuarine Heatwave'.

modellIn addition to SST, the temperature of an estuarine water body is controlled by its depth, the water temperature of all freshwater tributaries, the temperature of the surrounding land forms, air temperature and the surface energy balance. As a result, water temperature dynamics of an estuary directly depend on its geomorphic type and hydrological regime.

For instance, in estuaries with very little exchange of oceanic waters such as ICOLLs, water temperatures are more affected by the surface energy budget as compared to more connected systems. The complex combination of temperature drivers makes it difficult to project future temperature extremes faced by estuaries and some form of modeling is required to get reasonable estimates. Module-3 provides a detailed description of modeling approaches, which are then put into practice in Module-6. Even though accurate projections require some form of modeling, observed water temperatures in NSW estuaries have increased already and there is likely that they will continue to reach unprecedented levels in the future.

For the Hunter Estuary, the temperature of the Hunter River, its major freshwater tributary, has increased by 1.1°C between 1996 and 2016 (Fig. 11). Together with projected increases in air and ocean temperature, these increases in upland and downstream boundary water temperatures provide increasingly favourable conditions for severe estuarine heatwaves. Despite long-term temperature records being limited, available records for NSW estuaries indicate significant temperature increases.

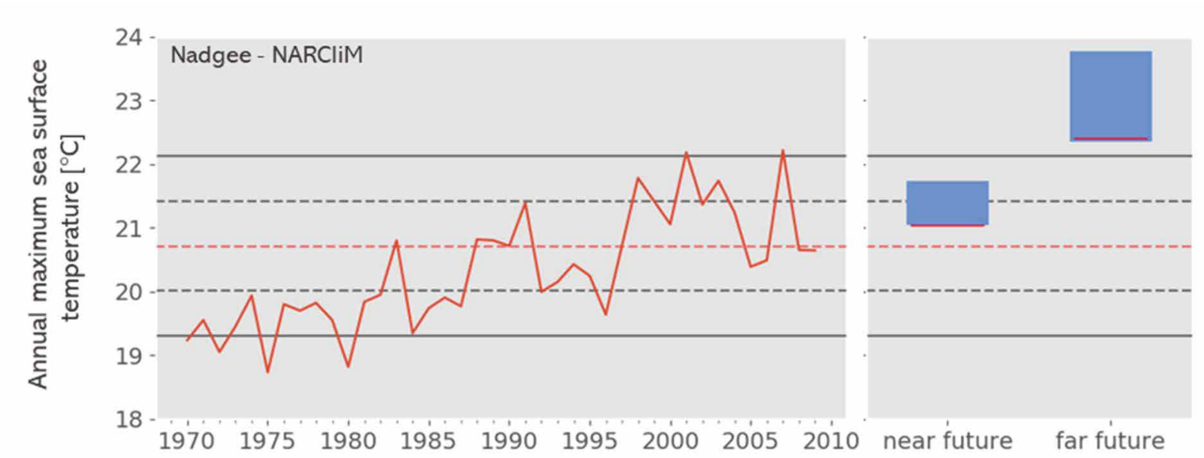


Fig. 13: NARCliM projections of changes in the annual maximum sea surface temperature compared to the present-day period (offshore Nadgee, NSW). Present day data and variability (horizontal lines representing median ±1 & 2 standard deviations) is based on NCEP/NCAR reanalysis data[40] used in NARCliM.

4.3 Sea level rise

Observed and future sea level trends have been the topic of extensive research. It is now broadly accepted that global sea levels have risen over the past two centuries.[21] Following a relatively stable period, global sea levels began to rise during the 19th century and have continued to rise throughout the 20th century.

Changes in averages: Sea levels can vary significantly on global and regional scales due to the relative influence and superposition of the multiple global and regional driving processes (i.e. ENSO, thermal expansion). The combination of these processes produces a complex pattern of total sea level change that varies through time.[27] As such, it is important to recognise that while global mean values of sea levels can be a useful indicator of sea level rise trends, regional factors can contribute to sea level rise and significantly influence observations and projections on a local scale. Figure 14 shows the observed monthly mean sea level at Fort Denison, Sydney Harbour for the period 1923-2018. Despite multiple multiyear periods of decreasing trends and a long period of relative stagnation between 1960 and1990, mean sea levels have increased at a rate of 1.3 mm per year over the almost 100 year-long period (~12 cm) at this location. More importantly, there has been an acceleration in the rise of mean sea levels in the last two decades (see exponential shape of smooth trends in Figure 14 from late 1990s onwards). This is in line with similar trends observed all around Australia[23] and at the global level.[22]

The data and trends in Figure 14 are based on observed water level data and hence, some of the variability shown is the result of variability in the ENSO cycle and other driving processes. After correcting for processes that interact with the average increase in global mean sea level, the rate of recent sea level rise around Australia (1993-2009) becomes 3.4 ± 0.4 mm per year, which is in line with global trends.[23] Due to the regional variability in sea level rise around Australia, the assessment of sea level rise impacts in NSW estuaries requires regionally relevant projections. Figure 15 shows the projected sea levels corresponding to the four RCPs averaged along the NSW coast.[27]

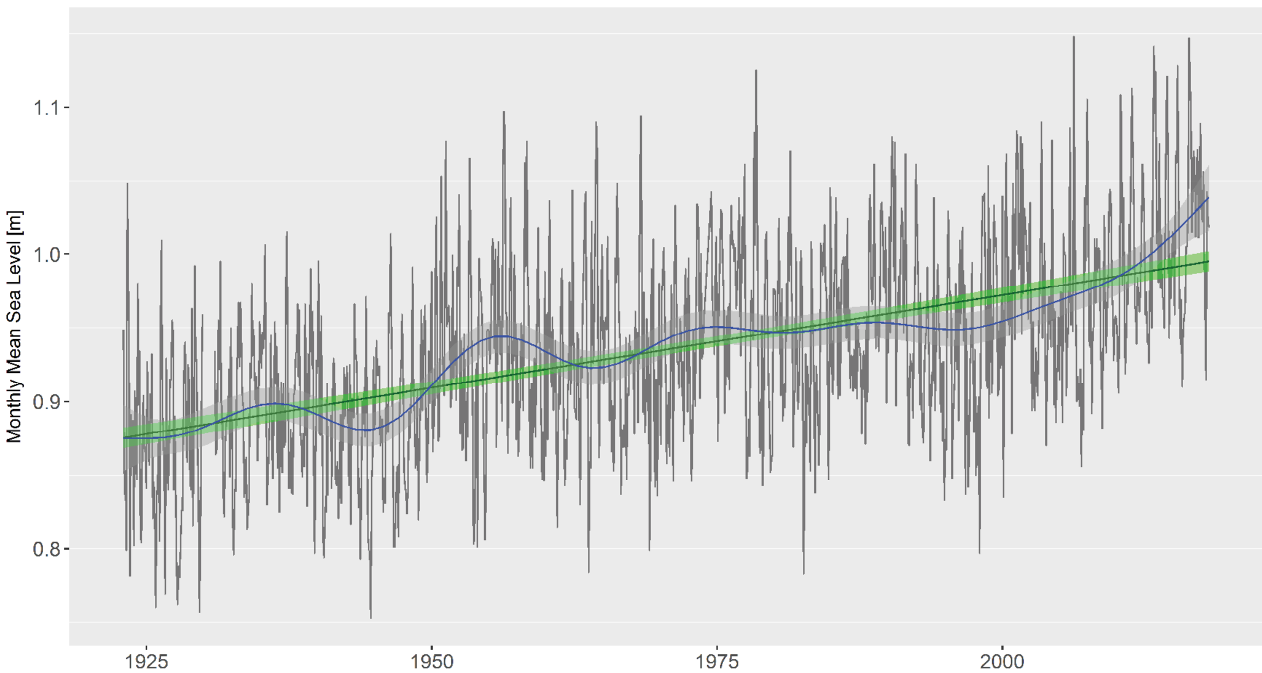


Fig. 14: Monthly mean sea levels at Fort Denison, Sydney Harbour with linear (green) and non-linear (blue) trends. The linear trend for 1924-2018 was 1.27 mm year-1 with $p<0.0005$. Non-linear trends are generated using the GAM data smoothing technique.[20] Data source: Bureau of Meteorology[41]

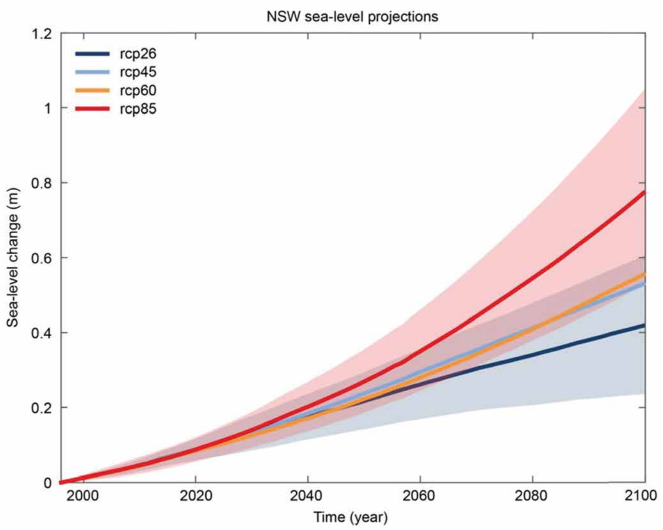


Fig. 15: Sea level rise projections averaged along the NSW coast for the four IPCC representative concentration pathways, (relative to the 1986-2005 baseline).[19]

Projections indicate that sea level rise will continue through the 21st century and beyond (for all emission scenarios but particularly for the unmitigated RCP8.5 scenario).[19] The intermediate scenarios (RCP4.5 and RCP6.0), which require substantial mitigation of greenhouse gas emissions, have intermediate values of rise by 2100. For the strong mitigation scenario (RCP2.6), the rise along the NSW coast is slightly lower than the global average. The emission scenario used in the NARCliM ensemble is comparable to the RCP8.5 scenario and consequently, the NARCliM-based climate change impacts presented in this chapter are likely to be accompanied with a sea level rise of around 50 cm (possibly 70 cm) for the far future period (1960 -1979). These sea level rise projections along the NSW are slightly higher than the global average sea level rise.[19]

Sea levels along the NSW coast have risen by around 15 cm since 1900 and are likely to rise by another 50 cm by 2080 without significant climate change mitigation efforts on a global scale.

Similar to the impacts of rising sea surface temperatures, the effects of rising sea levels to estuarine water levels and hydrodynamics are unique for each estuary and largely depend on its particular geomorphic type and corresponding tidal regime. The entrance size, length, width and depth of an estuary affects the propagation of tides along the waterbody.[24] Quantifying changes to estuarine water levels (i.e. second order impacts) from changes in coastal mean sea levels (i.e. first order impacts) requires modeling and available approaches are presented in Module-3. Rising sea levels can affect many estuarine processes including water depth, hydrodynamics and mixing, salinity intrusion and sediment dynamics and geomorphology. Making accurate and locally-relevant projections of water levels and hydroperiods typically requires detailed hydrodynamic modeling. An example of this type of model for quantifying climate change impacts on water levels, salinity and temperature is presented in Module-6.

Changes in extremes: Extreme sea levels are of particular interest to coastal zone managers and planners since they can have significant impacts on infrastructure and ecosystems along the coast and within estuaries. Sea levels are affected by regular and irregular processes associated with planetary motions, ocean waves, oceanic currents, meteorological factors, and geological phenomena. Extreme sea levels rarely occur due to a singular process, but, more commonly, result from a combination of several processes occurring over varying temporal and spatial scales as shown in Figure 16.[35] As a result, when assessing the exposure to sea level rise, the combined effect of these factors requires detailed analysis to interpret historic observations and future projections.

Extreme sea levels are the result of the combined effects of longer-term sea level variability (i.e. seasonal, interannual, decadal), tides, storm surges, wave setup and wave runup. All of these processes cause increases of water levels on top of the long-term mean sea levels. Rises in mean sea level due to climate change can be seen as an increase in the baseline that does not directly affect the factors that drive extreme sea levels. That means that under RCP8.5, an extreme sea level that historically occurred once in 50 years, will be up to 50cm higher by 2080 compared to 1990 due to mean sea level rise. This, however, assumes that the processes that drive extreme sea levels do not change as a result of climate change. In reality, climate change can lead to changes in the longer-term variability of sea levels, storm surges and wave set-up. The storm surge and wave set-up components are largely driven by coastal storms and historic and future changes in east coast low climatology, as discussed below. The long-term variability of sea levels is driven by large-scale oceanic processes and longer-term oscillations in the climate and ocean system that can cause sea level anomalies.

Sea level anomalies (often referred to as tidal anomalies) describe the differences between the actual water and predicted water level(s). Anomalies can include a combination of short-term factors, such as variations in seasonal temperature, air pressure, wind stress, and coastal-trapped waves and longer-term effects caused by variations in global atmospheric and oceanic patterns. A comprehensive summary of sea level anomalies along the NSW coastline is discussed in Modra and Hesse (2011).[36] A study conducted by the Manly Hydraulics Laboratory[37] showed that sea level anomalies of up to 0.5m can occur during the course of an event. Future projections of the processes that drive longer-term sea level anomalies remain sparse and are subject to a high level of uncertainty.

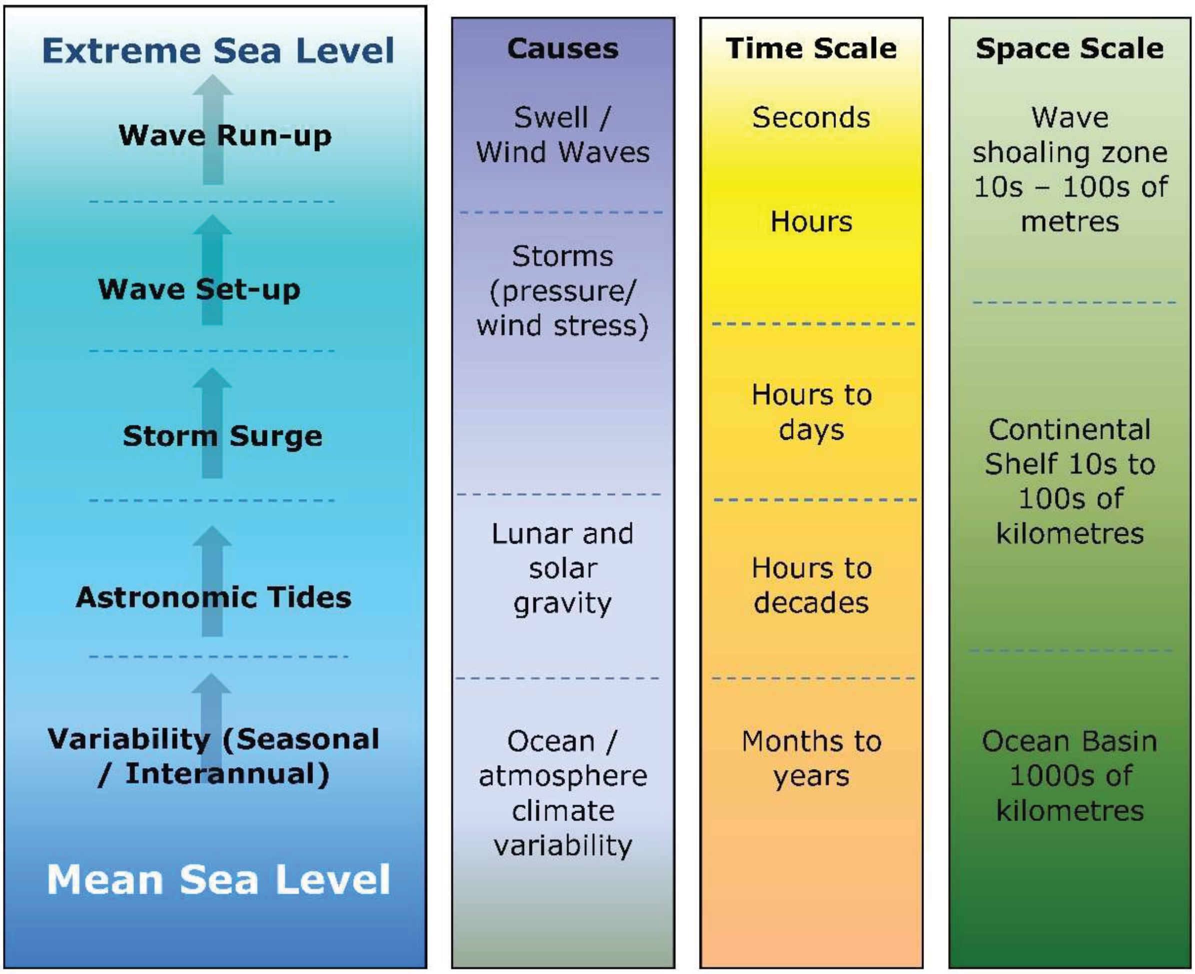


Fig. 16: Contributions to extreme sea levels at the coast after McInnes et al. (2016)[35]

4.4 Ocean pH and salinity

Oceanic acidity is increasing around Australia and along the NSW coast in line with global increases in atmospheric carbon dioxide.[4] Atmospheric carbon dioxide concentration is commonly measured in partial pressures expressed as µatm and this concentration is projected to increase to around 500 µatm by 2050 and 940 µatm by 2100 from the pre-industrial level of 280 µatm under the high emission scenario.[27] Increasing carbon dioxide concentrations in the atmosphere that drive global warming also leads to increasing levels of carbon dioxide in the oceans. The absorption of additional carbon dioxide by the oceans changes the chemistry of the water causing an increase in adicity (decrease in water pH) along with an increase in the solubility of carbonate minerals that are important for the shells and skeletons of many marine organisms.

The pH of the global ocean surface waters varies considerably across time and space but is commonly in the range of 7.8 and 8.4.[27] The present trend of oceanic acidification ranges between -0.0013 and -0.0024 pH units per year across the globe and these trends can differ substantially for different locations.[27] Future trends of ocean acidification will largely depend on the level of future carbon dioxide emissions, which was shown for different RCPs in Fig. 3. Under the high emission scenario, global average decreases of around 0.42 pH values are projected for the end of this century.[27] Importantly, pH levels within estuaries often exhibit high levels of variability within and between years, due to the influences of urban or agricultural runoff, acid sulfate soils, algal blooms and blackwater events (details are provided in Module-3). For the NSW coast, projected decreases in pH are -0.32 [-0.33 (10th percentile) to -0.31 (90th percentile)]. Figure 17 shows that such decreases in average pH will lead to a future baseline (long-term average) that is outside the envelopes of historic variability. Considering that the acidity dynamics (i.e. developmental inputs) in the estuary remain at recent historic levels, this increase in the baseline acidity could therefore lead to adverse impacts to estuarine ecosystems.

For sea surface salinity, GCM projections used by Climate Change in Australia are -0.02 [-0.16 (10th percentile) to 1.85 (90th percentile)] in the practical salinity unit (psu).[4] The salinity concentration in open oceans is typically around 35 psu,[27] whereas in estuaries, it can vary from less than 1 psu near freshwater inflows from rivers to much higher than 35 psu in enclosed shallow water bodies that undergo evapoconcentration. Considering this very high level of natural variability, the slight decreases in ocean surface salinity projected for the open ocean is unlikely to impact estuarine salinity too dramatically. Instead, changes in mean sea levles, evapo-transpiration and rainfall are likely to have more significant impacts on estuarine salinity.

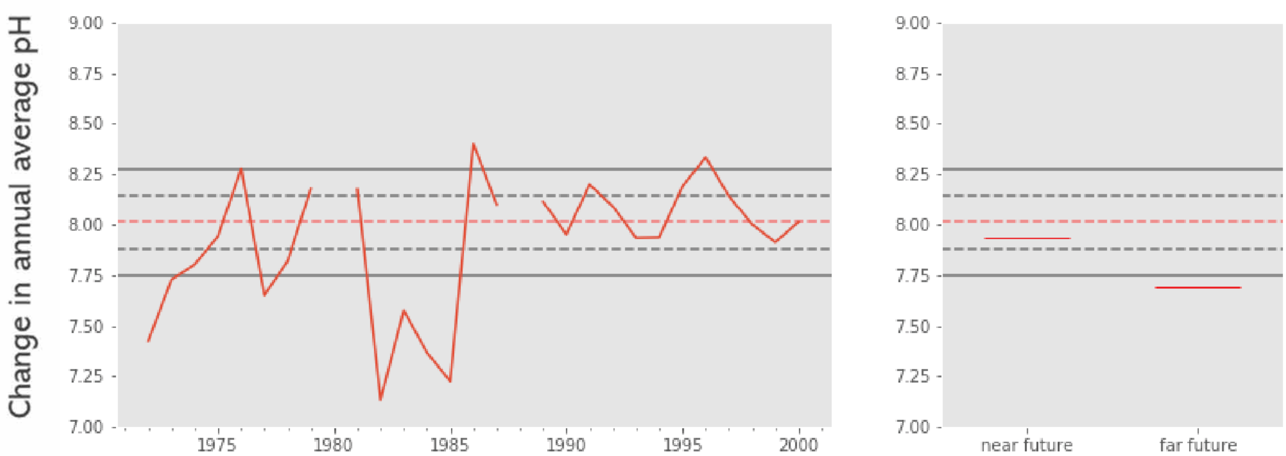
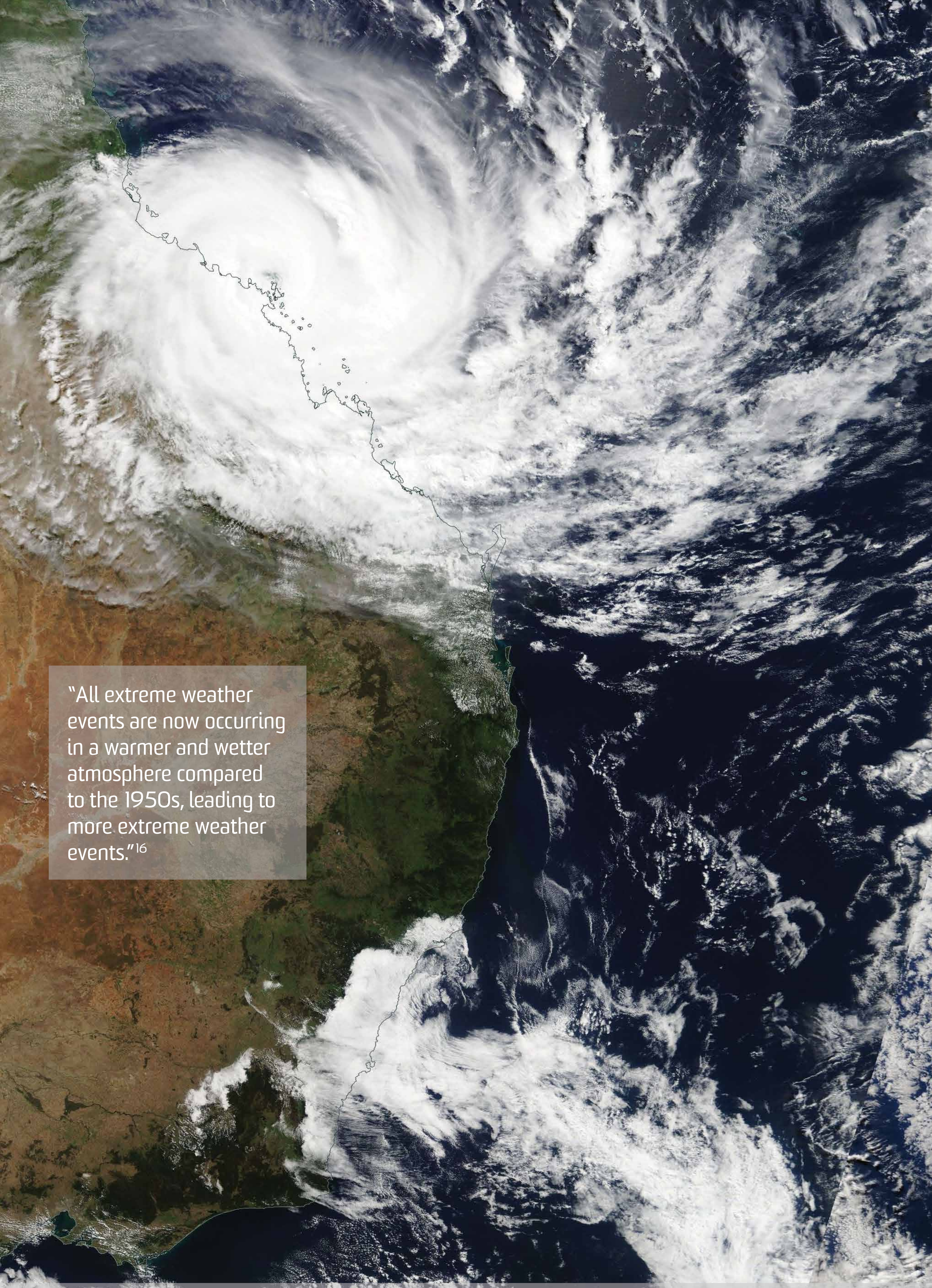


Fig. 17: Projections of changes in the annual average sea surface pH compared to the historic pH levels[4] and variability inside the Hunter River Estuary, NSW (horizontal lines representing median ±1 & 2 standard deviations). Source of in-situ pH data: NSW Department of Primary Industries. Future projections: Climate Change in Australia (Marine Explorer)[4]



"All extreme weather events are now occurring in a warmer and wetter atmosphere compared to the 1950s, leading to more extreme weather events."[16]

MODIS view of Cyclone Debbie, 28th of March 2017, source: NASA Worldview

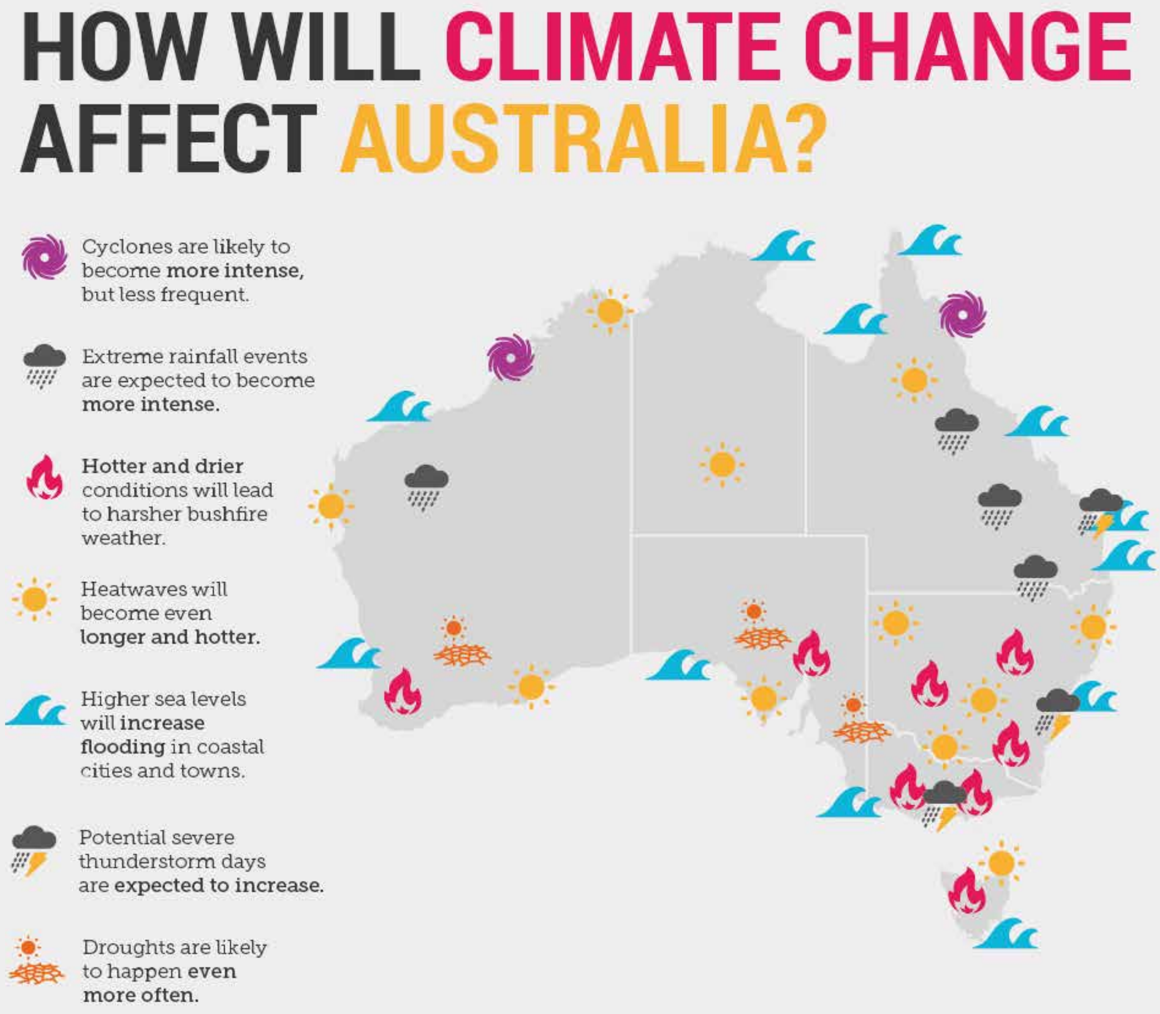
BOX-3: A synthesis report on extreme weather in Australia

Cranking Up The Intensity: Climate Change And Extreme Weather Events

Steffen, W., Hughes, L., Alexander, D., & Rice, M. (2017).[16] *Available at:* https://www.climatecouncil.org.au/

Understanding changes in weather extremes due to climate change is critical for estuarine management and adaptation planning. Written by the Climate Council, an independent crowd-funded organization, this report provides an illustrative summary of weather extremes in Australia and the role of climate change in these extremes. The key findings of the report are:

- "Climate change is influencing all extreme weather events in Australia."[16]
- "Some of the most severe climate impacts the world has experienced have occurred in 2016."[16]
- "Across Australia, extreme weather events are projected to worsen as the climate warms further."[16]
- "The impacts of extreme weather events will likely become much worse unless global greenhouse gas emissions are reduced rapidly and deeply."[16]



4.5 Rainfall

Processes producing rainfall are often very localized (i.e. associated with fine-scale topography) and can change over very short time scales. As such, GCMs typically do not reproduce observed rainfall data well. It is often stated that confidence in GCM projections of temperature is greater than the confidence in projections of rainfall. Due to these uncertainties, projections of future rainfall should be used and interpreted with caution. As illustrated in Box-2, regional climate models have consistent errors in predicting rainfall amounts and intensities. To address these errors, it is common practice to postprocess model outputs so that the statistical properties of the simulated amounts match the observed statistics, a process known as bias correction. This bias correction has been applied to rainfall and air temperature outputs of the entire NARCliM ensemble. The bias corrected NARCliM data currently represents the most fine-scaled projections for future rainfall climates across NSW.

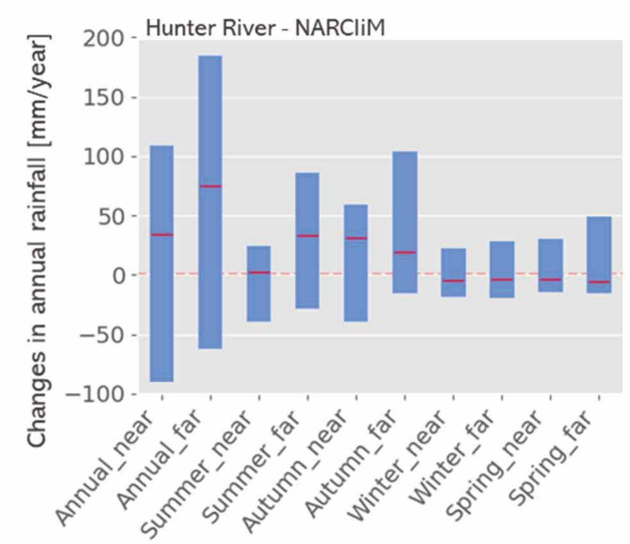


Fig. 18: NARCliM projections of changes in annual and seasonal rainfall for the near and far future for the Hunter River Estuary.

Changes in averages: So what changes are to be expected for rainfall across the NSW coast according to the bias corrected NARCliM rainfall data? As shown in Figure 18, projections for total annual rainfalls range from small decreases to substantial increases. As shown in Box-2, these changes appear largely insignificant when compared to the natural interannual variability. The largest increases in average rainfall are projected for the summer and autumn seasons. In Box 2 it was shown that rainfall can change in several ways as a result of climate change. Changes in extreme rainfall are particularly relevant for estuaries.

Changes in extremes: It is now well established that as the climate warms, heavy rainfalls tend to become even more extreme.[32] This increase in the intensities of extreme rainfalls can be observed in historic weather data for the last century. This trend towards more intense extreme rainfalls is captured well by the NARCliM ensemble, which projects a continuation of the increasing trends that are observed over the past century.[30]

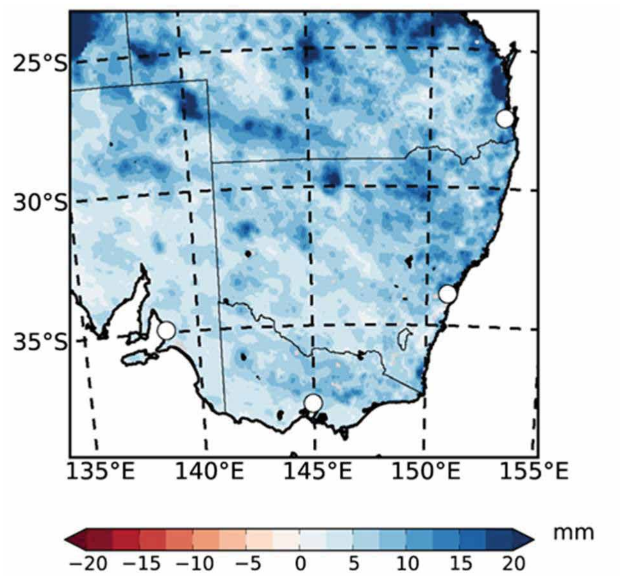


Fig. 19: NARCliM ensemble mean changes between the present day (1990–2009) and far future (2060–2079) in annual maximum 1-day precipitation[30]

Extreme indices (introduced in Box-2), can be used to highlight and summarize changes in the frequency and intensity of extreme events from GCM or RCM climate projection data. Examples of these indices include the monthly or annual maximum 1-day precipitation or the maximum number of consecutive wet or dry days. The changes between the present day (1990–2009) and far future (2060–2079) maximum annual 1-day precipitation across the NARCliM region are shown in Figure 19. These changes are calculated using the same method as presented in Box-2. For the Australian East Coast, average increases of over 10mm in annual maximum 1-day rainfalls are projected.[30] These changes are seen across the majority of extreme rainfall indices and the projected increases in the intensity of extreme rainfall events will likely be accompanied by more frequent floods in estuaries and their tributaries. However, as seen in Figure 18, these projections are not very robust and subject to a high level of uncertainty.

> "… changes in the nature of the precipitation regime will present water resource managers with challenges not encountered in the historical record and emphasises the need to include more than just annual mean future changes in their planning processes." [30]

Changes in dry spells: Another important projection of the NARCliM ensemble is that the length of maximum dry spells (number of consecutive days with <1 mm rainfall per year) is likely to increase in the future, while the maximum length of consecutive wet spells will likely remain at present day levels.[30] The changes in the length of maximum consecutive dry spells between the far future and present-day period as projected by the NARCliM ensemble are shown in Figure 20. While coastal areas between Brisbane and Sydney are experiencing minor increases in the length of dry spells (with the exception of coastal catchments in the Great Dividing Range), the southern NSW coast is facing increases of up to more than four days on average. So while the majority of estuaries and respective catchments across NSW are facing insignificant changes in the amount of annual rainfall, more rain will fall during increasingly intense extreme rainfall events, while the length of consecutive dry spells is also increasing.

This combination of more extreme rainfalls and longer dry spells is sometimes referred to as hydroclimatic intensity. The NARCliM projections and their implications can be summarized as follows:

"While not all members of the ensemble agree that this increase is significant, the combination of longer dry spells and increases in extreme precipitation magnitude indicate an important change in the character of the precipitation time series. This could have significant hydrological implications since changes in the sequencing of events can be just as important as changes in event magnitude for hydrological impacts." [30]

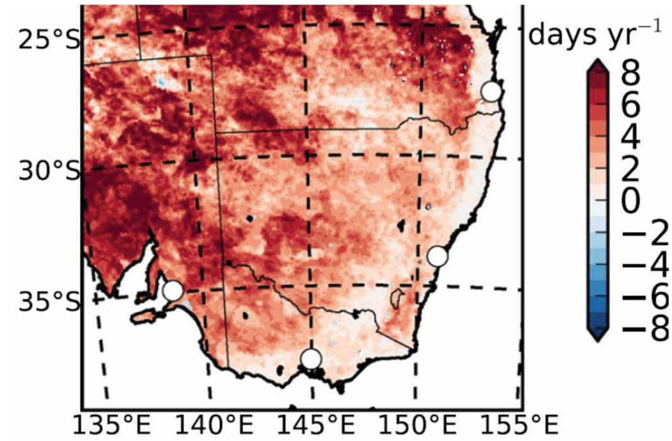


Fig. 20: NARCliM ensemble mean changes between the present day (1990–2009) and far future (2060–2079) in the length of annual maximum dry spell[30]

Changes in extreme rainfall in applied coastal flood risk management: The standard guideline for the design of flood protection infrastructure and the required catchment and flood modeling in Australia is the Australian Rainfall and Runoff (ARR) (http://arr.ga.gov.au/). Australian Rainfall and Runoff provides the latest design rainfall intensity-frequency-duration curves, which are used as the basis for designing flood protection infrastructure. Intensity-duration-frequency curves are built based on observed climate data and hence, designing flood protection infrastructure for the upcoming century requires the consideration of the effects of climate change on rainfall climatology and ultimately intensity-frequency-duration curves. A comprehensive study was conducted to update the Australian Rainfall and Runoff recommendations for adjusting intensity-frequency-duration curves for climate change.[28] Using two very high-resolution RCMs and bias correction, the study found that for the greater Sydney region, the probability of a currently once in 100 year 24-hour rainfall event will increase by up to 20% by 2050,[28] a trend that is likely representative for the majority of the NSW coast. Currently, the Australian Rainfall and Runoff suggests an increase of 5% per °C atmospheric warming to be applied to the intensity-frequency-duration curves. For the Lake Nadgee example, the median increase in average temperature of 1.8°C would require an increase of 9% to be applied to the design rainfalls.

4.6 Winds, waves and storms

Around 57% of major floods in Australian east coast catchments (including NSW estuaries) are caused by midlatitude cyclones commonly called East Coast Lows (ECLs).[26] ECLs are also the major force behind extreme wave events and storm surges and hence, potential changes in ECL climatology (number, frequency, intensity and timing of ECLs over long time periods) are likely going to have a significant impact on estuaries.

A recent study has tested how the NARCliM ensemble can reproduce observed ECL climatology.[31] The study tested how individual models as well as the ensemble mean can reproduce observed ECL climatology and found that the ensemble mean consistently performs well. The study also found that without RCM downscaling, the GCMs do a poor job in representing ECLs, with the more extreme observed ECLs not being represented at all. This means that the NARCliM ensemble is suitable for studying ECLs and future storm climate across the NSW coast, and can generate useful projections for extreme ECLs. In summary, the future storm climate that NARCliM projects for the NSW coastline is one with similar or potentially slightly increased numbers of ECLs during the summer months and less ECLs in the winter months, which is when they most commonly occur presently. The decrease in winter ECLs is due to the well established poleward shift of the midlatitude storm belt that climate change is causing.[4] These numbers, however, are the average numbers over the entire area where ECLs typically occur (see Figure 21).

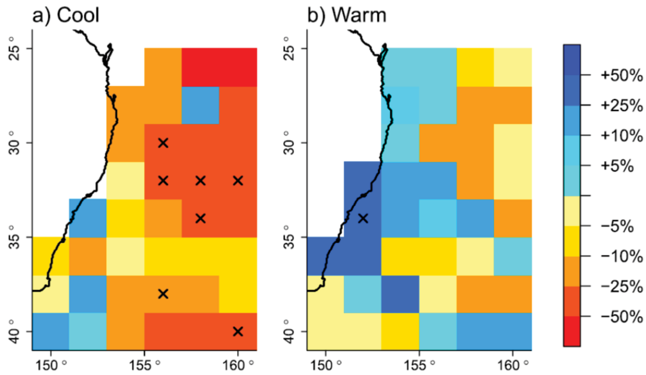


Fig. 21: NARCliM ensemble mean changes between present day (1990–2009) and far future (2060–2079) in the number of ECLs during the cool and warm period. Cells marked with a cross had a statistically significant trend.[31]

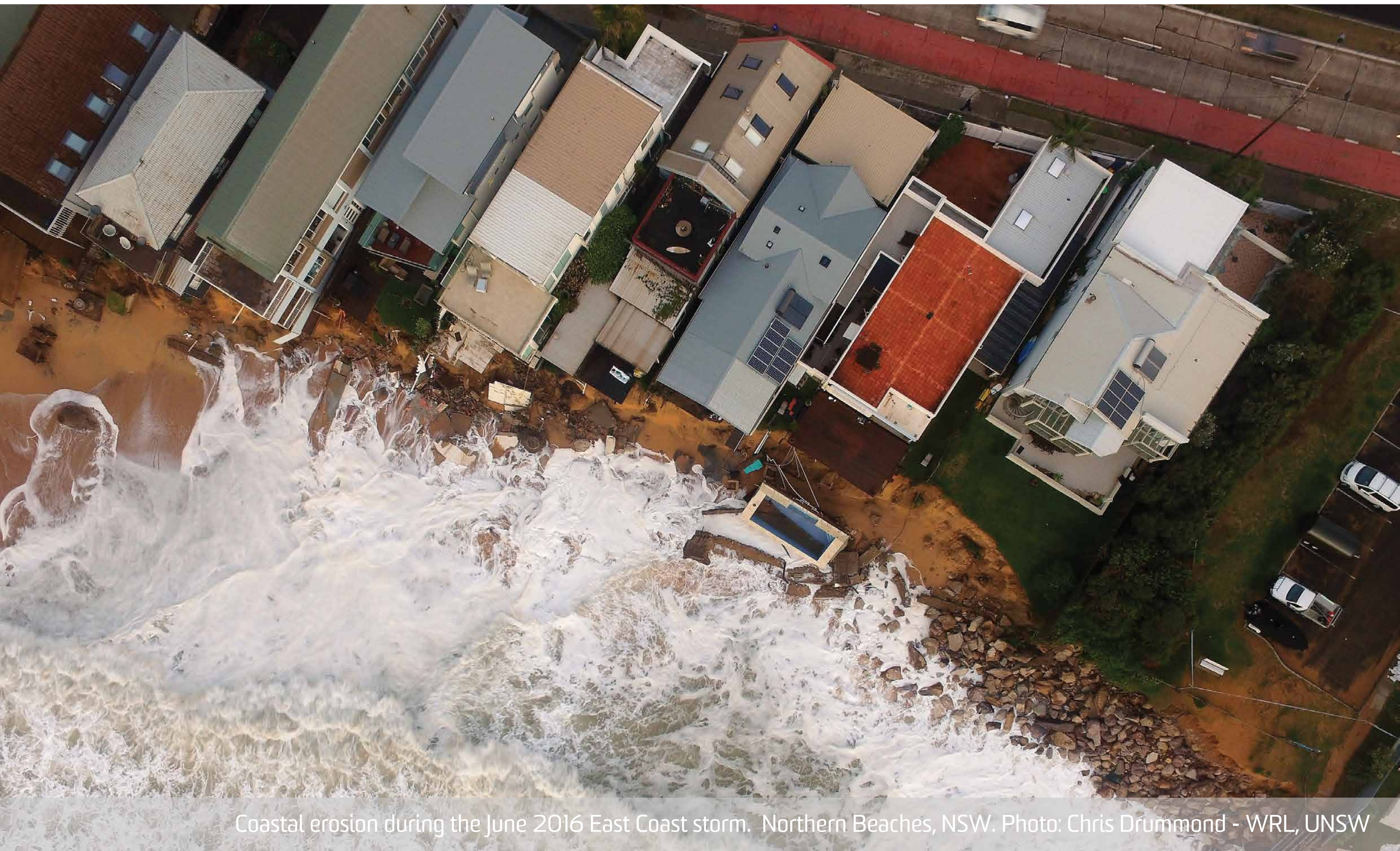
Extreme waves during the June 2016 East Coast storm. Northern Beaches, NSW. Photo: Larry Paice - WRL, UNSW

When focusing on storms in close proximity to the Australian East Coast, there is clear trend towards more ECLs during summer and small decreases (including one area with a small increase) during winter. A projection by NARCliM that is particularly relevant for NSW estuaries is an increase in ECLs that cause very heavy rainfalls and flooding over the coastal zone while at the same time, there might be a potential decline in ECLs that cause extreme winds.[31]

A comprehensive study performed by researchers from the Bureau of Meteorology in 2014 analysed likely changes to the wave climate on the Australian East Coast.[29] They analysed a total of 18 GCM projections and historical wave data and conclude that it is very likely that there will be a significantly reduced number of large wave events in the future. Despite a reduction in the number of large wave events, the authors note that those events that occur in the future might be more intense and that sea level rise could lead to compounding effects.[29] The combination of potentially more intense extreme wave events with rising sea levels might increase the likelihood of unprecedented storm surge events affecting estuaries.

4.7 Summary of climatic changes

A summary of all relevant climatic changes affecting estuaries along the NSW coastline that were discussed in this section is provided in Table 1 on the next two pages. For each of the discussed climate drivers, the table provides recent historic trends along with near and far future projections. Colour coding is used to illustrate the confidence level associated with the projections. Where possible, projections were generated from the NARCliM ensemble or, where not possible, taken from other peer-reviewed literature and data sources. The table is intended to provide a cohesive and holistic overview of climatic changes along the NSW coastline and it is recommended to consult the provided references for detailed information on specific changes.



Coastal erosion during the June 2016 East Coast storm. Northern Beaches, NSW. Photo: Chris Drummond - WRL, UNSW

Table 1: Summary of observed and likely future changes in the NSW coastal climate

Variable	Trend	Summary of changes	Regional differences along the NSW coast
Air temperature	⇧	Average and extreme air temperatures have increased and are projected to continue to increase steadily along the NSW coast.[38,39] Heatwaves are projected to become more frequent and intense albeit at a slower rate compared to inland NSW.[15]	The warming signal (averages and extremes) appears to be less prounounced in the north: Historic incerase is +0.8°C in average temp. over South and Central Coast but only 0.5°C over far North Coast.[39]
Sea surface temperature	⇧	Largely-owed to the intensification of the East Australian Current, the Tasman Sea off NSW is a global hotspot of oceanic warming at three to four times the global rate.[14] Marine heatwaves are becoming more frequent and intense and sea surface temperature will continue to reach unseen maximum levels along the NSW coastline.[38]	Historic trends and future projections are more pronounced in the southern parts of the coastline. Observed increases in the hottest daily mean sea surface temp of each year 1950-2010 are 1.7°C for the northern, 2.5°C for the central and 2.8°C for the southern parts of the coast.[38]
Sea levels	⇧	NSW mean sea levels have risen by almost 10cm since 1900 and rates of rise are accelarating since 1990.[42,43] NSW mean sea levels exhibit natural longer-term variability but will likely continue to rise at an accelarating rate, potentially reaching up to 1m by 2100.[35,43] Increases in future extreme sea levels are mainly the result of mean sea level rise.[48]	Mean sea levels can be considered to rise uniformly along the NSW coastline.[43] Extreme sea level events are often driven by East Coast Lows, for which increases are possible in summer over the southern parts of the coast due to the more pronounced changes in sea surface temp in the southern Tasman Sea.[44]
Ocean acidity	⇧	Oceanic acidity is increasing globally driven by increasing CO_2 concentrations in the atmosphere. Current global trends are decreases between -0.0013 and -0.0024 pH units per year and future decreases in pH off NSW will largely depend on future CO_2 emissions.[27]	Oceanic acidification various regionally (across large oceans) but pH levels and the projected changes can be considered uniform along the NSW coastline[4]
Rainfall	⇕	Both decreases and increases in total annual rainfalls are possible along the NSW coast and there is a projected change in the seasonality, with less rain falling in winter and spring and more during summer and autumn.[38] More of the rain is likely going to fall at higher intensities and the length of dry spells is increasing.[30] Extreme precipitation events associated with East Coast Lows might increase in the future.[44]	No pronounced differences in the projected changes in average and extreme precipitation and the length of dry spells along the coast from north to south[30]. Changes in rainfall regimes can vary locally due to topographic features such as the Great Dividing Range along the NSW coastline[30].
Winds, storms & waves	⇕	Observed and future changes in average winds and waves along the NSW coastline are small.[18,29] For East Coast Lows (ECLs), which drive extreme winds, waves and sea levels, there is a) very high level of natural inter-annual and inter-decadal variability and a lack of significant observed trends,[50] b) likely future reductions in winter ECLs due to the poleward shift of the midlatitude storm track,[18,19,29] c) possible future increases in summer ECLs and corresponding extreme rainfalls along the NSW coast[19,44] and the intensity of the most severe storms.[51]	The largest increases in the number of summer East Coast Lows are expected for the southern part of the NSW coastline, due to the largest increases in sea surface temperatures observed here.[44] Due to a poleward shift of circulation features that are critical for storm generation such as the tropical Hadley Cell, the midlatitude storm track and the Eastern Australian Current, non-uniform changes in storm, wave and wind cilmate along the NSW coastline are likely.[4]

Legend

High Confidence
Climate models can reproduce observed changes in this variable well and/or there is generally good agreement within the model ensemble and/or the projected changes are well in line with well-established theories of physical climate science.

Medium Confidence
Climate models can reproduce observed changes in this variable reasonably well and/or there is reasonable agreement within the model ensemble and/or the projected changes are generally in line with well-established theories of physical climate science.

Low Confidence
Climate models reproduce observed changes in this variable poorly and/or there is poor agreement within the model ensemble and/or the projected changes are not always consistent with established theories of physical climate science.

	Observed changes 1950-2010*	Projected near future change by 2030***	Projected far future change by 2080***
Average	**+0.8°C** in average temp[39]	**+0.7 [0.5; 0.8]°C** in average temp**	**+1.9 [1.6; 2.3]°C** in average temp**
Extremes	**+1.3°C** in the hottest day of the year max temp[39]	**+1.3 [-0.2; 1.9]°C** in hottest daily max temp of the year.** More frequent and intense heatwaves[15]	**+2.9 [1.8; 3.5]°C** in hottest daily max temp of the year.** More frequent and intense heatwaves[15]
Average	**+1.5°C** in average temp**	**+0.7 [0.4,0.9]°C** in average temp**	**+2.2 [1.5,2.4]°C** in average temp**
Extremes	**+2.5°C** in the hottest daily mean sea surface temp of the yea**	**+0.6 [0.6; 1.8]°C** in hottest daily mean sea surface temp of the year**	**+2.0 [1.8; 3.4]°C** in hottest daily mean sea surface temp of the year**
Average	**+3.5 cm (+8.5 cm since 1914)** in Sydney Harbour without controling for long-term variability[41]	**+14 [10-19]cm**[43]	**+45 [31-59]cm**[43]
Extremes	Extreme sea levels increased more rapidly than mean sea levels since 1897 in Perth and since 1914 in Sydney.[46]	Minimal change to the existing sea level anomaly variability. Weather and circulation changes as a result of climate change are unlikely to cause large changes in the frequency and magnitude of extreme sea levels in addition to the changes caused by mean sea level rise.[48]	
Average	**-0.1 pH** units decrease in the global ocean since pre-industrial levels, equalling an increase of 26% in hydrogen ions[27]	**-0.08 [-0.08 to -0.07] pH** units decrease; RCP8.5 CMIP-5 ensemble; 1995-2005 baseline[4]	**-0.32 [-0.33 to -0.31] pH** units decrease; RCP8.5 CMIP-5 ensemble; 1995-2005 baseline[4]
Extremes	-	-	-
Average	No significant trend in total annual rainfalls[39]	**+34 [-90,109]mm** in annual rainfall. Increases in autumn rainfall and decreases in winter and spring rainfalls**,[30]	**+76 [-62,185]mm** in annual rainfall. Increases in summer and autumn rainfall and decreases in winter and spring rainfalls**,[30]
Extremes	**-3 days** less per year with at least 20mm of rain[39] **+30mm** in the maximum daily rainfall per year[39]	**No increase** in days with at least 20mm of rainfall** **+5 [-12, 28]mm** in the maximum daily rainfall per year**	**No increase** in days with more than 20mm of rainfall** **+10[-1, 24]mm** in the maximum daily rainfall per year**
Average	No significant trends in average winds.[4] Small increases in average wave heights (1970-2010) for mid-north and small decreases for the south coast.[45,47]	Projected changes in average annual wind speeds for 2080-2099 (compared to 1995-2005 baseline) range from -5% to +5% with the median being close to 0.[4] Possibly small decreases in the average significant wave height along most of the NSW coast.[49] Changes in the wind climate may lead to changes in the average wave direction.	
Extremes	No significant trends in East Coast Lows and extreme winds. Small increases in average wave heights (1970-2010) for mid-north coast and small decreases for south coast.[45,47]	The number of ECLs in winter is projected to decrease, while the number of summer ECLs close to the NSW coastline and the intensity of the most severe storms is projected to increase.[11,18,19] Possible increase of ECLs that bring sever rainfall along the NSW coastal fringe.[19] Possibly fewer large storms and wave events along the NSW coast but the most severe storm and wave events are likely to become more extreme in the future.[29]	

* Observed changes are given for the Hunter River Estuary site [32.751 South; 151.690 East], near Newcastle on the New South Wales Central Coast,

** Unless otherwise specified, projected changes are calculated directly from the NARCliM[38] regional climate model ensemble for the Hunter River Estuary site [32.751 South; 151.690 East] near Newcastle on the New South Wales Central Coast, and given as the median[10th and 90th percentile] of ensemble changes compared to the 1990-2010 baseline. Observed trends and future projections for sea surface temperatures are calculated from the NCEP/NCAR reanalysis dataset.[40]

*** The near future (2020-2039) projections represent the best estimate of future climate by 2030, even with significant global mitigation measures.[15,38]
The far future (2060-2079) projections are more sensitive to changes in global emissions but still represent the current best estimate of our future climate by 2070.[15,38]

References

1. IPCC, 2014. Climate Change 2014 - Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. doi:10.1017/CBO9781107415324

2. https://www.ipcc.ch/publications_and_data/-ar4/wg1/en/ch2s2-10-2.html.

3. http://4hiroshimas.com/#Science

4. CSIRO and Bureau of Meteorology, 2015. Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia.

5. IPCC, 2000. Summary for Policymakers: Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Group. doi:92-9169-113-5

6. Evans, J. P., Ji, F., Lee, C., Smith, P., Argüeso, D., & Fita, L. (2014). Design of a regional climate modelling projection ensemble experiment - NARCliM. Geoscientific Model Development, 7(2), 621–629. https://doi.org/10.5194/gmd-7-621-2014

7. http://www.ipcc.ch/report/ar4/

8. https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM/CMIP3-vs-CMIP5

9. Olson, R., Evans, J. P., Argüeso, D., & Di Luca, A. (2014). NARCliM Climatological Atlas, 1–423.

10. Evans, J. P., Ji, F., & Change, C. (2012). NARCliM Technical Note 1 Choosing GCMs, (October), 1–7.

11. World Meteorological Organization. (2008). Bulletin: Adapting to climate variability and change (Vol. 57 (2)).

12. van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: An overview. Climatic Change, 109(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z

13. Office of Environment and Heritage. (2015). New South Wales Climate change snapshot Overview of New South Wales climate change.

14. Perkins-Kirkpatrick, S. E., White, C. J., Alexander, L. V., Argüeso, D., Boschat, G., Cowan, T., et al. (2016). Natural hazards in Australia: heatwaves. Climatic Change, 139(1), 101–114. https://doi.org/10.1007/s10584-016-1650-0

15. NSW Office of Environment and Heritage. (2015). Heatwaves Climate Change Impact Snapshot.

16. Steffen, W., Hughes, L., Alexander, D., & Rice, M. (2017). Cranking Up The Intensity: Climate Change And Extreme Weather Events. Retrieved from https://www.climatecouncil.org.au/uploads/1b331044fb03fd0997c4a4946705606b.pdf

17. Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., et al. (2016). A hierarchical approach to defining marine heatwaves. Progress in Oceanography, 141, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

18. Wernberg, T., Smale, D. A., Tuya, F., Thomsen, M. S., Langlois, T. J., Bettignies, T. De, et al. (2012). An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nature Climate Change, 3(1), 78–82. https://doi.org/10.1038/nclimate1627

19. Glamore, W. C., Rahman, P. F., Cox, R. J., Church, J. A., & Monselesan, D. P. (2019). Sea Level Rise Science and Synthesis for NSW NSW Office of Environment and Heritage's Coastal Processes.

20. Wood, S. N. (2017). Generalized Additive Models: An Introduction with R (Second Edi). Chapman and Hall/CRC.

21. Church, J. A., Clark, P., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. and Unnikrishnan, A. S. (2013). "Chapter 13: Sea Level Change". Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth

Assessment Report of the Intergovernmental Panel on Climate Change.

22. Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/PNAS.1717312115

23. White, N. J., Haigh, I. D., Church, J. A., Koen, T., Watson, C. S., Pritchard, T. R., et al. (2014). Australian sea levels-Trends, regional variability and influencing factors. Earth-Science Reviews, 136(October), 155–174. https://doi.org/10.1016/j.earscirev.2014.05.011

24. Hanslow, D. J., Morris, B. D., Foulsham, E., & Kinsela, M. A. (2018). A Regional Scale Approach to Assessing Current and Potential Future Exposure to Tidal Inundation in Different Types of Estuaries. Scientific Reports, (December 2017), 1–13. https://doi.org/10.1038/s41598-018-25410-y

25. Roy, P. S., Williams, R. J., Jones, A. R., Yassini, I., Gibbs, P. J., Coates, B., et al. (2001). Structure and function of south-east Australian estuaries. Estuarine, Coastal and Shelf Science, 53(3), 351–384. https://doi.org/10.1006/ecss.2001.0796

26. Callaghan, J., Power, S., 2014. Major coastal flooding in southeastern Australia, associated deaths and weather systems. Aust. Meteorol. Oceanogr. J. 64, 183–213. doi:10.22499/2.6403.002

27. Pörtner, H. O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., et al. (2015). Ocean Systems. In Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects (pp. 411–484). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415379.011

28. Chiew, F., Vaze, J., Viney, N., Jordan, P., Perraud, J., Zang, L., Teng, J., Arancibia, J.P., Morden, R., Freebairn, A., Austin, J., Hill, P., Wiesemfeld, C., Murphy, R., 2008. Rainfall-runoff modelling across the Murray-Darling Basin A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project.

29. Dowdy, A.J., Mills, G.A., Timbal, B., Wang, Y., 2014. Fewer large waves projected for eastern Australia due to decreasing storminess. Nat. Clim. Chang. 4, 283–286. doi:10.1038/nclimate2142

30. Evans, J.P., Argueso, D., Olson, R., Di Luca, A., 2017. Bias-corrected regional climate projections of extreme rainfall in south-east Australia. Theor. Appl. Climatol. 130, 1085–1098. doi:10.1007/s00704-016-1949-9

31. Luca, A. Di, Evans, J.P., Pepler, A.S., Alexander, L. V, Argüeso, D., 2016. Evaluating the representation of Australian East Coast Lows in a regional climate model ensemble. J. South. Hemisph. Earth Syst. Sci. 66, 108–124.

32. Wasko, C., Sharma, A., 2015. Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. Nat. Geosci. 8, 527–529. doi:10.1038/ngeo2456

33. Institution of Engineers Australia. (2015). Australian Rainfall Runoff PROJECT 1 Development of Intensity-Frequency-Duration Information across Australia. Climate Change Research Plan Project STAGE 3 REPORT P1/S3/001. https://doi.org/10.1038/103447b0

34. Institution of Engineers Australia PROJECT 1, Of, D., & Across, 2015). Australian Rainfall Runoff. Climate Change Research Plan Project STAGE 3 REPORT P1/S3/001, (December), 62 pages. https://doi.org/10.1038/103447b0

35. McInnes, K. L., White, C. J., Haigh, I. D., Hemer, M. A., Hoeke, R. K., Holbrook, N. J., et al., 2016. Natural hazards in Australia: sea level and coastal extremes. Climatic Change, 139(1), 69–83. https://doi.org/10.1007/s10584-016-1647-8

36. Modra, B. and Hesse, S., 2011. "NSW ocean water levels". NSW Coastal Conference Tweed Heads.

37. MHL, 2015. Nsw Ocean And River Entrance Tidal Levels Annual Summary 2014–2015. Manly Hydraulics Laboratory. Report MHL2384.

38. Olson, R., Evans, J. P., Di Luca, A., & Argüeso, D. (2016). The NARCliM project: Model agreement and significance of climate projections. Climate

Research, 69(3), 209–227. https://doi.org/10.3354/cr01403

39. SILO, Scientific information for land owners - The State of Queensland (Department of Environment and Science) 1995–2018; available at: https://silo.longpaddock.qld.gov.au/

40. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. I., S. Saha, et a. (1996). The NCEP/NCAR 40-Year Reanalysis Project E. Bulletin of the American Meteorological Society

41. Fort Denison monthly tide gauge data, Bureau of Meteorology, http://www.bom.gov.au/oceanography/projects/ntc/monthly/

42. Couriel, E., Public, N. S. W., Manly, W., Modra, B., Public, N. S. W., Manly, W., et al. (2014). NSW Sea Level Trends – The Ups and Downs, 1–19.

43. Mcinnes, K. L., Church, J., Monselesan, D., Hunter, J. R., & Grady, J. G. O. (2015). Information for Australian Impact and Adaptation Planning in response to Sea-level Rise. Australian Meteorological and Oceanographic Journal, (October), 1–46. https://doi.org/10.22499/2.6501.009

44. Pepler, A. S., Luca, A. Di, Ji, F., Alexander, L. V, Evans, J. P., & Sherwood, S. C. (2016). Cyclones During the 21St Century. Geophysical Research Letters, 43(1), 334–340. https://doi.org/10.1002/2015GL067267.Received

45. Wave buoy data for the NSW coast: NSW Office of Environment and Heritage, NSW Coastal Data Network Program; available at http://www.mhl.nsw.gov.au/data

46. Church JA, Hunter JR, McInnes KL, White NJ (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. Aust Meteorol Mag 55:253–260

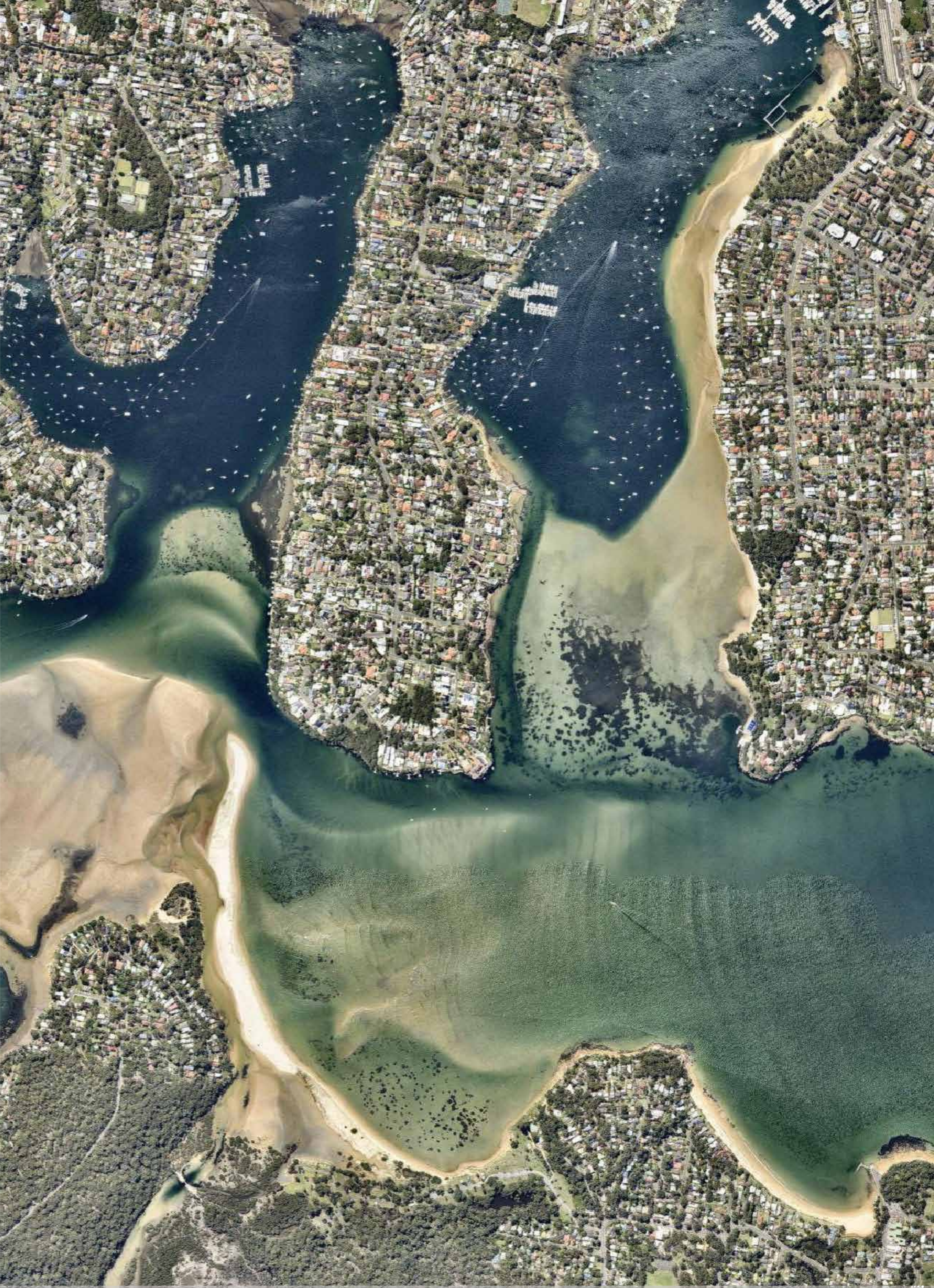
47. Shand, T. D., Carley, J. T., You, Z. J., & Cox, R. J. (2011). Long-term trends in NSW coastal wave climate and derivation of extreme design storms. NSW Coastal Conference, 2(Figure 1), 8–11.

48. Colberg F, McInnes KL (2012) The impact of future changes in weather patterns on extreme sea levels over southern Australia. J Geophys Res Oceans 117, C08001. doi:10.1029/2012jc007919

49. Hemer MA, Fan Y, Mori N, Semedo A, Wang XL (2013c) Projected changes in wave climate from a multi- model ensemble. Nat Clim. Change advance online publication. http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1791.html#supplementary-information

50. Pepler, A., Coutts-Smith, A., & Timbal, B. (2014). The role of East Coast Lows on rainfall patterns and inter-annual variability across the East Coast of Australia. International Journal of Climatology, 34(4), 1011–1021. https://doi.org/10.1002/joc.3741

51. GROSE, M., POOK, M., MCINTOSH, P., RISBEY, J. & BINDOFF, N. 2012. The simulation of cutoff lows in a regional climate model: reliability and future trends. Climate Dynamics, 39, 445-459.



Port Hacking – Tide dominated drowned valley – [-34.076, 151.138]