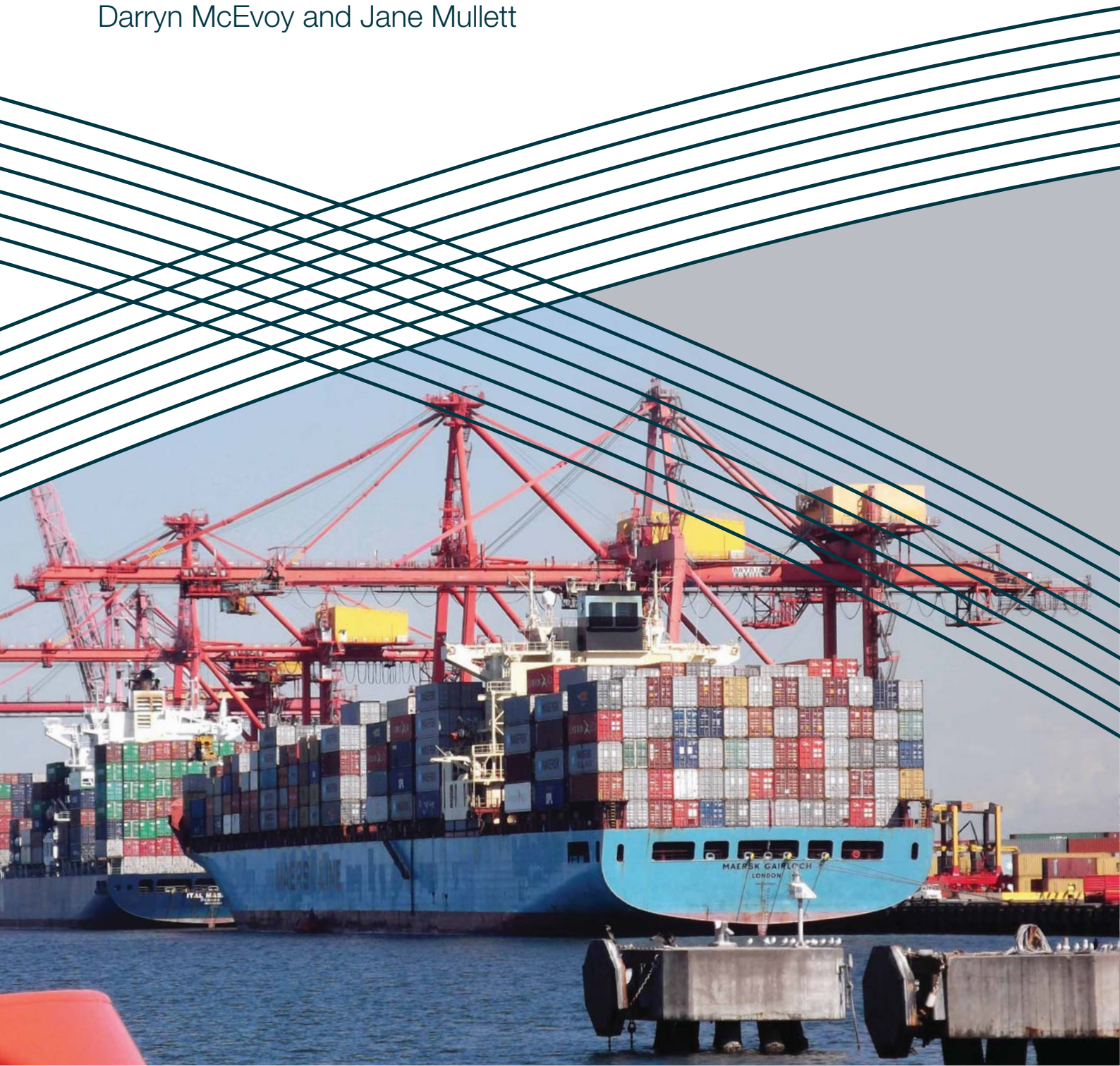


Enhancing the resilience of seaports to a changing climate: Research synthesis and implications for policy and practice

Work Package 4 of Enhancing the resilience of seaports to a changing climate report series

Darryn McEvoy and Jane Mullett



Enhancing the resilience of seaports to a changing climate: Research synthesis and implications for policy and practice

**Work Package 4 of
Enhancing the resilience of seaports
to a changing climate report series**

RMIT University

AUTHORS

Darryn McEvoy

Jane Mullett



Published by the National Climate Change Adaptation Research Facility 2013

ISBN: 978-1-921609-82-4 NCCARF Publication 11/13

Australian copyright law applies. For permission to reproduce any part of this document, please approach the authors.

Please cite this report as:

McEvoy, D & Mullett, J 2013, *Enhancing the resilience of seaports to a changing climate: Research synthesis and implications for policy and practice. Work Package 4 of Enhancing the resilience of seaports to a changing climate report series*, National Climate Change Adaptation Research Facility, Gold Coast, 49 pp.

Acknowledgements

This work was carried out with financial support from the Australian Government (Department of Climate Change and Energy Efficiency) and the National Climate Change Adaptation Research Facility.

The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

The authors would like to acknowledge the time and commitment of all the information providers and stakeholders that were involved in the project and actively contributed to the co-generation of knowledge. Particular thanks go to the CSIRO and the BoM, the case study ports, and key stakeholders; comprising Ports Australia, Transport & Logistics Industry Skills Council, Shipping Australia Limited, and the Maritime Union of Australia. Additional matching funds provided by RMIT University, the University of Queensland, and the Transport & Logistics Industry Skills Council also contributed to the program of research. Finally, we would also like to thank the anonymous referees for their valued comments and insights.

Material contained in this report has been distilled from the following technical reports:

- WP1 – *Understanding future risks to ports in Australia*, Enhancing the resilience of seaports to a changing climate report series (authors: Darryn McEvoy, Jane Mullett, Sophie Millin, Helen Scott, Alexei Trundle)
- WP2 – *Functional resilience of port environs in a changing climate – Assets and operations*, Enhancing the resilience of seaports to a changing climate report series (authors: Prem Chhetri, Jonathan Cocoran, Victor Gekara, Brian Corbitt, Nilmini Wickramasinghe, Gaya Jayatilleke, Fatima Basic, Helen Scott, Alex Manzoni, Chris Maddox)
- WP3 – *Structural resilience of core port infrastructure in a changing climate*, Enhancing the resilience of seaports to a changing climate report series (authors: Daniel Kong, Sujeev a Setunge, Tom Molyneaux, Guomin Zhang, David Law)

Disclaimer

The views expressed herein are not necessarily the views of the Commonwealth or NCCARF, and neither the Commonwealth nor NCCARF accept responsibility for information or advice contained herein.

Cover image: Patrick Wharf, Port of Brisbane © Climate Change Adaptation Program, RMIT University

TABLE OF CONTENTS

ABSTRACT	3
EXECUTIVE SUMMARY	4
1. INTRODUCTION	9
2. CLIMATE CHANGE AND SEAPORTS	10
3. PROJECT OUTLINE	12
4. THE CASE STUDY PORTS	13
5. STAKEHOLDER ENGAGEMENT	15
6. WORK PACKAGE 1: UNDERSTANDING FUTURE RISKS	17
6.1 ANALYSING PORTS AS SYSTEMS.....	18
6.2 CURRENT (AND PAST) CLIMATE/WEATHER DATA AND EXTREME EVENTS	18
6.3 FUTURE CLIMATE DATA	19
6.4 RECONCILING CLIMATE INFORMATION WITH RESEARCH / END-USER NEEDS	22
6.5 NON-CLIMATE DRIVERS	24
7. WORK PACKAGE 2: FUNCTIONAL RESILIENCE OF THE PORT ENVIRONS	25
7.1 ASSET REGISTER, VULNERABILITY ASSESSMENT, AND VISUALISATION.....	25
7.2 SIMULATING THE POSSIBLE IMPACT OF EXTREME EVENTS ON PORT OPERATIONS.....	26
7.3 PORT WORKFORCE ADAPTIVE CAPACITY	29
8. WORK PACKAGE 3: STRUCTURAL RESILIENCE OF CORE PORT INFRASTRUCTURE	31
8.1 ASSET IDENTIFICATION AND DETERIORATION MODELLING	31
8.2 MODELLING RESULTS.....	32
8.3 DECISION SUPPORT TOOLS.....	34
9. ADAPTATION GUIDELINES	36
9.1 VULNERABILITY / RISK ASSESSMENT	36
9.2 ADAPTATION OPTIONS.....	37
10. IMPLICATIONS FOR POLICY, PRACTICE AND FURTHER RESEARCH	39
10.1 EVIDENCE FROM THE PORT CASE STUDIES	39
10.2 MAKING SENSE OF THE CLIMATE SCIENCE	40
10.3 UNDERTAKING AN INTEGRATED ASSESSMENT OF RISKS.....	41
10.4 ADAPTATION OPPORTUNITIES	42
REFERENCES	43
APPENDIX 1: LIST OF PROJECT STAKEHOLDERS	46
APPENDIX 2: CLIMATE INFORMATION PACKS FOR THE CASE STUDY PORTS	49

List of figures

<i>Figure 1: Location of case study ports (Ports Australia, n.d.)</i>	14
<i>Figure 2: Potential climate impacts on different sub-components of the port system</i>	18
<i>Figure 3: Gladstone. Ozclim grid cells: 1° Buffer (0.5° radius)</i>	22
<i>Figure 4: System agents and their interaction</i>	27
<i>Figure 5: Elements of adaptive capacity</i>	29

List of tables

<i>Table 1: Models used to represent different climate futures for the case study ports</i>	20
<i>Table 2: Weather variables of most concern to port tenants and the impacts on the workflow</i>	28
<i>Table 3: Modelling scenarios</i>	28

ABSTRACT

This report synthesises the research findings from the 'Climate Resilient Seaports' project funded by NCCARF and conducted between 2011 and 2012. The intention of the project was to contribute to an emerging knowledge base relating to climate change and seaports, to test and refine assessment methodologies, and to develop tools to assist decision-making by port personnel. The discussion contained in this report draws directly from the research carried out for the three work packages. These include: 1) understanding future risks, 2) functional resilience of the port environs, and 3) structural resilience of core port infrastructure. As a synthesis document, the intellectual capital and inputs from each of the project teams is fully acknowledged. The report concludes with some reflections on the key challenges and opportunities facing researchers, policymakers and practitioners in making Australia's seaports more resilient to future risks.

EXECUTIVE SUMMARY

This synthesis report focuses on the resilience of seaports; critical components of the national infrastructure portfolio that are considered vital to the functioning of Australia. However, whilst there is considerable emphasis placed on the strategic importance of ports – and the need for anticipatory planning to ensure a sustainable national ports system in the future – the interpretation of climate information for adaptation planning and its integration into policy and practical decision-making processes remains at an embryonic stage. In response, the project ‘Enhancing the Resilience of Seaports to a Changing Climate’ was commissioned by the National Climate Change Adaptation Research Facility (NCCARF) to address this important emergent agenda.

The analysis, carried out over a 21-month period (2011–12), was undertaken by a multi-disciplinary research team from two universities (RMIT University, supported by the University of Queensland) in close consultation with key stakeholders. Central to the research carried out was an integrated assessment of the climate and non-climate risks that are likely to affect future port operations; information that was then distilled to inform the assessment of vulnerabilities and adaptation options for different ‘elements at risk’ within the port environs (infrastructure, functional assets, and workforce). Work package reports are available for these. Three ports along Australia’s eastern seaboard, representative of different port types and climatic regimes, were used as case studies to test and refine the various assessment tools and methodologies.

Future risks

The sourcing and interpretation of future climate information proved to be a considerable challenge; ultimately requiring an iterative learning approach that sought to match the climate data currently available from the latest scientific global climate models (GCMs) with the desired inputs for the logistical and engineering assessments (bridging the climate science – adaptation planning divide). This activity involved close working with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology (BoM), as well as advice from other academic experts. The suite of climate models that was used in the project resulted from the application of CSIRO’s framework ‘Climate Futures’. This enabled the choice of a set of possible futures (described for this project as most likely, hotter and drier, cooler and wetter) that encompassed a range of possible modelled ‘futures’ most appropriate for the geographical locations and for the likely climate risks. This method also helped to support the choice of a comprehensive and internally consistent set of models.

However, not all data requested by each of the work packages was available (or easily accessible) from the current state-of-the-art climate modelling efforts and therefore a hybrid approach was necessary (e.g. additional ‘best guess’ inputs, informed from other modelling studies, were used in the engineering deterioration modelling for variables that were not available). It is also worth noting that the operational concerns of the port authorities were found to be predominantly on the seaward-side (moving and mooring, loading and unloading ships). Further analysis is needed for those climate-related variables that are less easily modelled (wind, wave, current etc.).

Recognising that climate change is only one of the many drivers affecting the functioning of ports, the project also drew on key national and sectoral documentation to frame and explore the non-climate drivers that are likely to impact on seaports in the near to medium term. The variables considered were: demography, economy, technology, institutions, and supply chains. Full detail is available in the Work Package 1 report.

Functional vulnerability

To ensure a comprehensive, system-wide analysis the project assessed the functional vulnerabilities of ports; considering the impact of extreme weather-related events on functional assets, the movement of goods, and the preparedness / adaptive capacity of the workforce (Work Package 2). Due to the difficulty of forecasting how ports will operate in the distant future, analysis needed to be framed by a relatively short time horizon (2030), with greater emphasis on the impacts of current day extreme events and how ports are managing these risks today. Hence, a more immediate emphasis was used as a starting point before forecasting over a shorter time period (addressing current day adaptation deficits). This vulnerability-led approach also compensates for the still-emerging knowledge base on the likely frequency (average return period) and intensity of future extreme events; as well as being a time frame more relevant to port authority decision-making processes.

Three deliverables were produced as part of the analysis on functional assets: firstly, vulnerability matrices for key areas of all three case study ports were developed (resulting in a transferable methodology for other ports); and secondly, two prototype models were built. The first of these was GIS-based (a tool for visualising key vulnerabilities – however a GIS-based approach proved to be both time and resource intensive and is therefore best suited to a more detailed assessment of risks that have been identified and ranked as priorities rather than as a first pass assessment). The second was an agent-based simulation which modelled the throughput of containers in a port environment when perturbed by external stressors. Attention was also paid to the human dimension in this work package, with analysis of the adaptive capacity of the workforce informing the development of a training manual aimed at the different groups of actors involved with port operations.

Infrastructural vulnerability

For the purposes of this project, the engineering analysis concentrated on the long-term deterioration of infrastructure assets (Work Package 3). As such, consideration of catastrophic failure brought about by the impact of a low probability though high consequence extreme event was outside the scope of this particular piece of work (though worthy of separate study). The research consisted of several components: structural asset identification, interpretation of climate data, long term deterioration modelling taking account of changes to climatic variables, resilience matrices, a methodology for conducting life-cycle cost analysis, and the development of a software tool for use by port engineers. Findings from the deterioration model, adapted to account for the changing exposure and sensitivity of different materials (concrete, steel, timber) to environmental parameters, predict that climate change will affect the timing of maintenance requirements by ports (sensitivity analysis indicates concrete will be most impacted by temperature, marine timber by sea salinity, and steel by relative humidity). These impacts will lead to important business implications e.g. balancing future maintenance and capital budgets. A design and maintenance cost management methodology was also developed by the project to support decision-making in this regard.

Summary findings

The research activity carried out by the project and its different work packages, reinforced by engagement with the case study ports, indicates that resilience to current day climate variability is evident within the immediate port environment (at the level of individual organisations). This can be attributed to autonomous adaptation primarily as a result of a combination of regulatory and operational mechanisms such as OH&S requirements, risk management strategies, and incremental changes to practice brought about by the ports experience of weather-related events; rather than as part of a conscious adaptation strategy (with the exception of sea level rise and planning for

raised berthing structures). However, important vulnerabilities were also identified; with the seaward-side of operations and the supply chain hinterland found to be most affected by current climate variability (vulnerabilities which will intensify under a changing climate). It should also be noted that climate change may bring some benefits for individual ports – e.g. sea-level rise may allow the passage of ships with deeper draught; hence reducing the need for channel dredging in some ports.

Explicit assessment of future climate risks and adaptation planning for the longer-term was also less evident, apart from consideration of sea-level rise. Low probability, though high impact, events are also less well considered. Looking forward, although 'hard' infrastructure assets can be made more resilient by changing design and maintenance regimes (addressing sensitivity), land use planning is likely to become even more important under a changing climate (changing levels of exposure, combined with developmental drivers). Functional resources (assets and the workforce) are likely to become increasingly vulnerable due to likely increases in the frequency and intensity of extreme events. As such, consideration of future climate change impacts within current risk assessment and management processes would strengthen existing resilience, with adaptation measures integrated as part and parcel of normal investment cycles or maintenance regimes. Analysis also needs to look beyond the immediate port environs to consider wider supply chain issues (this is where the impact from recent extreme events has been greatest in the past e.g. storm and flooding affecting coal supply through the flooding of mines and washing out railway lines). Adaptation, in this regard, is likely to require the promotion of flexibility and spare capacity within the system, ultimately going against the grain of business 'efficiency'.

Findings from across the comprehensive program of research were collated and analysed to inform adaptation guidance for climate resilient seaports. This is embedded in a traditional risk management framework to best align with the sector's current risk management processes (involving step by step decision-support). Conducting a location specific climate risk assessment is recommended (as is now required by ports in the UK). The research outputs come at a particularly opportune moment with recent Federal Government endorsement of new national port and freight strategies in July and September of 2012. It is hoped that the various deliverables from the project therefore not only make a valuable contribution to the emerging international body of knowledge on climate change and the resilience of seaports, but also have a more practical impact through informing the Australian port sector's capacity to respond.

Headline messages

A number of headline messages arising from the research are worth highlighting up front. These include:

- Acting on future climate risks to seaports, particularly bridging the divide between the climate science and adaptation action, is a challenging endeavour. It involves matching output from the evolving climate models with the information needs of different port 'end users' in order to consider elements at risk at the local scale. As such, a hybrid approach involving multi-actor dialogue – in support of co-generation of knowledge – is necessary to underpin an effective assessment process. Such a participatory approach has been developed and showcased by this project.
- The seaward-side of operations (ship movement and mooring, loading and unloading) and the supply chain hinterland (road and rail movement, intermodal hubs) were found to be most affected by current climate variability. Continued research is needed into the modelling of seaward variables of concern, future

extreme events and possible consequences, and the impact on wider supply chains.

- One key challenge is how best to address the complexity and uncertainty inherent in the climate data. For instance, whilst climate-related extreme events are of primary concern to port authorities the scientific modelling of future extreme events remains uncertain. However, whilst not ideal, the uncertainty in modelling should not act as an impediment to actively considering potential impacts and no or low regret adaptation responses. A vulnerability-led approach focusing on current day variability is a useful foundation for initially considering longer-term risks.
- For this project, analysis of a range of possible futures (most likely, hot/dry, and cool/wet) was conducted in close collaboration with the CSIRO and informed by their 'Climate Futures' framework, ensuring there was consistency across the application of scenarios to each of the case study ports. This is a recommended resource for other similar assessments as it encourages an understanding of the range of possible climates, including those of low probability but high impact.
- The forthcoming IPCC 5th Assessment Report will introduce an updated set of climate data, in new formats, and it is important that Australian end-users (and project funders) align themselves with this new resource.
- Given the complexities involved, Federal resources should be invested in 'trusted' platforms that assist stakeholders in accessing climate data, and interpreting it for their risk assessment and adaptation needs (including guidance for dealing with uncertainty). With the necessary resources, this is either an extended role that CSIRO could valuably perform or else it could be tasked to a 'boundary' organisation responsible for tailoring climate information and guidance. Providing consistency in interpretation at the state level would be helpful.
- Linked to the point above, a nationally consistent approach to the data necessary for informing climate assessments (including variables such as sea-level rise) would be extremely beneficial. Support for knowledge transfer mechanisms should also be encouraged.
- Climate risks are only one set of drivers facing future port operations, and it is therefore valuable to contextualise climate risks within a broader set of drivers. For this project important non-climate drivers (demography, economy, technology, institutions, and supply chains) were addressed. However, integrating climate and non-climate scenarios is difficult partly as a result of their respective time horizons. Authoritative national level guidance on the use of non-climate scenarios would help to provide a common framework for future studies and would also support the development of the new National Freight and Port Strategies.
- Due to their importance as operational hubs, it is important that port authorities undertake assessment in partnership with other logistics providers and local/state/national governments to ensure a coordinated approach to long-term planning of land-use, factoring in "room to move" for ports and other critical infrastructure (e.g. transport supply chain routes).
- A policy requirement for major infrastructure owners and operators to conduct climate risk assessments and make them publicly accessible, as is now the case in the UK, is an option that should be actively considered.

- A major opportunity is available to integrate adaptation to climate change with the national and international mitigation agenda that has begun to be embraced by the seaport community e.g. a holistic approach to addressing climate change.
- This research project has developed a number of methodologies, tools, and outputs (including adaptation guidelines) that are intended to support assessment processes and adaptation interventions (both outcomes and strengthening adaptive capacity) by Australian seaports. Further detail is available in each of the project technical reports.
- As a consequence of the lessons learnt from this research project, follow-up activity (funded by the Australian National Data Service) is now being undertaken to design a web-based decision-support toolkit for Australian seaports that will help inform their adaptation planning. The proto-type is intended to be ready by mid-2013.

1. INTRODUCTION

In recent times there has been increasing emphasis on ensuring that Australia's critical infrastructure is resilient to the emergent challenges of the 21st Century. The contemporary focus on resilience is well illustrated by the introduction of an engineering 'report card' in 2005 which requires each State and Territory to carry out a five-yearly rating of the condition of their key infrastructural assets. In the latest round of assessments (Engineers Australia, 2010) it was noted that a combination of social and demographic change – particularly population growth forecasts for the major urban centres – and the projected impacts of a changing climate in the future, will place increasing strain on the country's infrastructure systems.

The significance of seaports is emphasised by the recent National Ports Strategy, which states that "ports and associated infrastructure are of the utmost economic and social importance to Australia" (Infrastructure Australia, 2011: 6); as framed by an overarching aim to "drive the development of efficient, sustainable ports and related freight logistics that together balance the needs of a growing Australian community and economy with the quality of life aspirations of the Australian people" (ibid: 7). However, as highlighted by the recently updated National Adaptation Research Plan for Settlements and Infrastructure (Cox et al, 2012), climate change will pose increasing challenges to the continuing successful operation of ports, and their associated infrastructure, over coming decades.

An integrated assessment of future climate risks – comprising quantitative, qualitative and participatory approaches – was conducted to determine the likely impacts on Australian seaports, to contextualise this information within the broader landscape of other non-climate drivers, and to scope out possible adaptation responses. Three case study ports were chosen for the detailed analysis. These were selected due to their location in different climatic regimes, as well as being representative of different port types (container versus bulk) with associated physical assets and logistical arrangements; hence maximising the potential transferability of project results to other Australian seaports.

To achieve its objectives, research activity was structured according to four discrete, though interlinked, work packages. The first of these (WP1) was to better understand the future risks (both climate and non-climate) and then to use this information to consider the resilience of three 'elements at risk' within the port environs: logistical functions and the workforce (the two elements combined within WP2) and infrastructural assets (WP3). This integrative summary report represents the main deliverable for WP4 (synthesis of activity and results). Written as a 'stand-alone' document, it provides commentary on the scope of the project, details methodologies and core deliverables for each of the work packages, before finally elaborating on the key findings and implications for both policy and practice. Adaptation guidelines for seaports were also produced. More comprehensive details on the activity carried out, and the research findings, are available in each of the individual reports as noted below.

- WP1 – Understanding future risks
- WP2 – Functional resilience of the port environs – assets and operations
- WP3 – Structural resilience of core port infrastructure
- WP4 – Synthesis
- Climate information packs for the case study ports (see appendices WP1 & 4)
- Adaptation guidelines

2. CLIMATE CHANGE AND SEAPORTS

Ports worldwide are now engaging with sustainability and greenhouse gas mitigation agendas to a much greater extent than previously (e.g. the Green Guide produced by the European Sea Ports Organisation, June 2012). In the Australian context, the peak industry body 'Ports Australia' has set up an Environment and Sustainability Group as part of its program of working groups to attempt to bring coherence to the raft of mitigation efforts, conservation and biodiversity initiatives, and broader 'green' port issues, which are now being implemented by Australian seaports. However, it is evident that much less attention has been paid to considering climate-related impacts, the future risks that a changing climate may bring (the exception being sea-level rise), and possible adaptation responses. This is an important knowledge gap that this project sought to address.

From the academic and grey literature review that was carried out it was found that although the topic is relatively new, with limited international studies on 'climate change and seaports' to date, a knowledge base is slowly beginning to develop. Worthy of academic note is the international analysis of exposure to sea level rise that was released by the World Bank and the OECD in 2008. This bench mark study – consisting of 136 ports, of which 5 ports were Australian – mapped the port cities considered most vulnerable to climate change impacts in 2070 (Nicholls et al, 2008). Analysis was based on a one in one hundred (1:100) year storm surge as the definitive water level from which to base calculations; with exposure of population and assets then estimated as a function of elevation against this water level (Hanson et al, 2011). Another international example, which adopted an alternative 'actor-based' approach, was the worldwide survey of Port Authorities that was undertaken by Becker et al (2011) to elicit information on the sector's risk perceptions, the likely impacts of climate change on future international port operations, and potential adaptation strategies.

Exemplar studies that have focused on the future impacts of climate change on international ports (and coastal zones more generally) include a follow up study by Nicholls et al (2010) which furthers the earlier analysis on sea level rise and storm surge by undertaking a preliminary economic costing of adaptation to sea level rise in coastal zones. Another key study was by Stenek et al (2011), which carried out a comprehensive analysis of the Cartagena port facility, Colombia. This piece of work was the only study uncovered by the literature review that takes a system-based and integrated approach; explicitly considering both the functional and infrastructure assets of the case-study port in its analysis. As such, it can be considered a pioneering system-wide effort to assess climate risks and adaptation options of international seaports in a comprehensive way.

Analysis of the grey literature indicated an increasing awareness of the need for port authorities to consider climate impacts as part of the broader spectrum of risks that need to be managed. For example, the World Association for Waterborne Transport Infrastructure (PIANC) responded to the findings of the IPCC 4th Assessment Report in 2007 by releasing a detailed paper that examined climate drivers and the potential impacts on maritime and inland navigation. It specifically explored potential responses to "infrastructure, vessels, and transport management in an effort to create a continuing dialogue for consideration of adaptation or mitigation strategies to climate change by the navigation community" (PIANC, 2008: 50). Other recent documents of importance include a review of climate change adaptation measures that are available to seaports (International Association of Ports and Harbors, 2011), and a growing number of climate risk assessments that have recently been carried out by ports in the UK (see for example, Peel Ports, 2011). Interestingly, this UK assessment activity was driven by

national legislation, in this case the UK Climate Change Act 2008, which requires all major seaports – as well as other infrastructure owners – to report to national Government on their climate risk assessments and identified adaptation measures. These reports are openly available on the Government website – promoting transparency within the sector and supporting peer learning (indeed, they acted as a valuable background resource to this project).

Whilst Australian seaports are not legally required to assess climate risks in such a way (though this remains a potential policy mechanism for promoting adaptation responses), there has been a marked shift in emphasis even during the recent lifetime of this project. For instance, climate change adaptation is explicitly addressed in Infrastructure Australia's fourth annual report to the Council of Australian Governments. Here, adaptation is defined as "assessing risks to infrastructure from extreme events, and understanding how asset management and the design and location of assets can be adapted in consideration of these risks" (Infrastructure Australia, 2012: 21). Though less explicit about climate change, the recent National Ports Strategy recommends that ports' planning documentation, with a suggested minimum time horizon of 15-30 years, should consider external factors (both risks and opportunities) that may impact on the functioning of ports (Infrastructure Australia, 2011).

In relative terms, as highlighted by Nicholls et al (2008), Australian ports are not considered to be at the same level of risk when compared to counterparts in the Asian and American regions. However, a salutary reflection is provided by a study of the city of Copenhagen (Hallegatte et al, 2008). Although not considered particularly vulnerable to coastal flooding, in the absence of protection the author estimated that "the total losses (direct and indirect) caused by the current 120-yr storm surge event, at 150 cm above normal sea level, would reach EUR 3 billion" (ibid: 3).

Whilst adaptation to future climate change is not high on the agendas of many Australian ports as yet, the research team's experience of engaging with the case study ports and other key stakeholders over the period of the project has shown that there was an openness to better understanding future climate risks, to engage in dialogue about the implications for the structural and functional resilience of ports, and to collaborate with research efforts that can help to inform how best to respond. This interest has been reinforced by the number of extreme weather events that have impacted Australian ports over the past few years; from the extended drought and heatwave of 2009 over south east Australia to the flooding in Queensland in 2010-11 and again in early 2013.

3. PROJECT OUTLINE

As stated in the original proposal, the overarching research objective was to 'better understand the vulnerability of critical seaport assets (structural and functional) and to develop new knowledge and methodologies for enhancing the resilience of seaports to future climate change'. This involved a multi-disciplinary, multi-institutional, effort to better understand climate-related impacts; to analyse how these will impact the structures and functioning of Australian seaports in the future; and to develop decision support guidance and tools that could support existing risk management strategies and contribute to more effective adaptation planning. To meet these objectives the project was therefore designed as a series of discrete, though interconnected, work packages.

Work package 1: Understanding future risks

The purpose of this 'foundation' work package, conducted by the Climate Change Adaptation Program at RMIT University, was to make sense of the complexity (and uncertainty) of the future risks that ports need to be planning for. The work involved close liaison with climate information providers [Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Climate Data Provision Service of the Bureau of Meteorology (BoM) and the Centre for Australian Weather and Climate Research (CAWCR)]; as well as the case study ports to ensure that the data and modelling efforts were informed by user needs. This was an iterative process with the translation of complex climate data into useable information proving to be a challenging endeavour. In addition, recognising that climate change will only be one of a set of stressors affecting future port operations, analysis also considered other socio-economic and institutional drivers with the potential to influence change.

Work package 2: Functional resilience of wider port environs

Ports are highly integrated operations with a complex set of logistics functions. Based on the need to promote adaptive ports which are adequately 'climate-proofed' for future conditions this work package first established a methodology for systematically identifying the vulnerability of functional assets in the wider port environs; then used this knowledge as a platform for considering issues of resilience according to: 1) port operations and freight distribution; 2) institutional adaptive management; and 3) workforce skills and preparedness. The research activity was carried out jointly between RMIT University (School of Business, IT and Logistics) and the University of Queensland (School of Geography, Planning and Environmental Management); resulting in a range of different deliverables (models, reports, recommendations for workforce training, and guidance on the development of adaptation strategies). It was decided that this last deliverable should be project-wide, rather than just related to 'functions', and hence was dealt with as a stand-alone adaptation guidance framework.

Work package 3: Structural resilience of core port infrastructure

This work package drew on engineering expertise at RMIT University (School of Civil, Environmental and Chemical Engineering) to consider the vulnerability of key infrastructure assets in the port precinct. Whilst simulation techniques and formulae are commonly used to estimate degradation of critical infrastructure when exposed to different environmental parameters (depth of high tide, temperature, wetting and drying cycles etc.) there has been little consideration of the altered levels of sensitivity and exposure that will result from changing climatic conditions. To address this limitation, deterioration models were derived for different materials that explicitly built in the effects of changing climatic variables; hence providing a practical tool for informing improvements to the management and design of core port infrastructure under a changing climate. This information was then used to inform the development of design and cost optimisation guidance for use by port engineers.

4. THE CASE STUDY PORTS

"Australia is an island continent with some 35,000 km of coastline ... stretch[ing] from latitudes of 11° S to 44° S ...[covering] the complete range of sea conditions possible, except ice. The tides vary in range from almost zero to some of the largest in the world ... The strongest swell possible impinges on our southern marginsThe northern coastlines in latitudes less than 25 degrees experience the ravages of tropical cyclones with their associated devastating storm surges" (Institution of Engineers, Australia, 2000: 5).

The case study focus of the research project was deliberately designed to account for the vulnerability of different port functions and infrastructure to a range of different climate risks. To this end, a systematic approach to port selection was adopted to ensure that a range of port operations across the Australian ports and a diversity of geographic and climatic conditions were represented.

The selection of ports was driven by the following criteria:

1. Representative of at least two different climatic regimes in Australia;
2. Account for a range of port operations, determined through the application of a functional typology screening process;
3. Linked to (2), immediate port environs to be comprised of different types of infrastructure;
4. Representative of different geographical settings;
5. Port's willingness to participate in the study.

Based on the above criteria, the port authorities that were selected as the case studies (listed from north to south) were: Gladstone Ports Corporation, Sydney Port Corporation, and Port Kembla Corporation (Figure 1). The ports are all found on the Eastern seaboard of Australia and are representative of two different climate zones: warm humid (Gladstone Port) and temperate (Sydney Port and Port Kembla).



Figure 1: Location of case study ports (Ports Australia, n.d.)

5. STAKEHOLDER ENGAGEMENT

From the earliest stages of the project it was recognised that effective engagement with a range of different actors (scientific experts from multiple disciplinary backgrounds, information providers, seaport authorities, practitioners, and policymakers) would be a critical element affecting the success of the program of research. Adopting a participatory approach was considered important in three main ways: firstly, to ensure that the project was cognisant of, and built upon, already existing knowledge (acknowledging the various research initiatives taking place both nationally and internationally); secondly, to promote access to – and interpretation of – the scientific data and information necessary for effective risk assessment and adaptation planning; and thirdly, to allow for iterative feedback during the lifetime of the project from the port authorities (as well as other stakeholders) to ensure that the deliverables were fit for purpose and practical application.

Academically, the project benefited from the guidance received from national and international experts; with their input particularly valued in the early stages when exploring some of the key methodological issues and data challenges that the project faced (a full list of contributors are shown in the appendix). In addition, the regular NCCARF thematic meetings convened by the 'Settlements and Infrastructure' network proved to be a valuable platform for benchmarking the progress of the project and providing informal scientific peer review. In terms of climate information provision, the CSIRO and BoM made substantial contributions to the project; and without their time and effort, advice, and provision of data, this project would not have been possible. Finally, the involvement of the three case study ports, and the support of the peak body 'Ports Australia', ensured that the analysis carried out was subjected to consistent scrutiny through a practitioner lens. Over the course of the research project, engagement with the ports included numerous meetings, interviews, and site visits in order to ground-truth data. Here again, the active engagement of stakeholders with the research being carried out was vital to the integrity of the project.

A series of six stakeholder workshops formed an integral part of the 'co-generation' of knowledge. Three of these were held in 2011 and were designed to inform the proposed research activity at an early stage. The first of these (Melbourne, July 2011) was convened to discuss the methodological and data challenges associated with assessing future climate risks (in the context of Australian seaports). Attendees included members of the CSIRO, BoM, CAWCR; with the conversations also benefiting from additional input from national and international climate risk experts who were present. This initial 'scientific' workshop established a valuable early framing for the research parameters, particularly with regards to the model selection process. Two further workshops were then held in Sydney (November 2011) and Melbourne (December 2011) in order to engage with a broader range of stakeholders; not only the case study port authorities but also other sector organisations associated with ports, transport, and supply chain logistics.

The Sydney workshop, which involved representatives from each of the case study ports as well as other key experts, proved to be a useful forum for interactive discussions and for the project team to receive feedback on appropriate analytical frameworks. Sessions were designed to introduce climate information – past and current data from the BoM and future scenario data from the CSIRO and State Governments – as well as allowing the attendees the opportunity to identify and discuss the vulnerability of key infrastructural and functional assets (and the perceived effectiveness of existing risk management strategies). An unexpected, though important, outcome of this early meeting derived from a debate on the selection of

climate models that were to inform the scenarios for each case study (the climate information introduced at the workshop had been based on a hotter and drier future and differed from scenarios advised by State Government in New South Wales). On the basis of this important difference (in relation to possible future rainfall) the project subsequently refined the suite of climate models that were to be included in the project to enable the consideration of a range of different climate futures (discussed further in this report in the section 'understanding future risks', and in more detail in the WP1 report).

The stakeholder meeting in Melbourne, held one month later, enabled the project team to engage with interested groups in the State of Victoria, to further test the assessment framework that was being developed, and to get additional feedback from a different group of stakeholders. This workshop also included a presentation by an international visitor from the Vrije Universiteit, Amsterdam, on the adaptation activity currently being carried out by the Port of Rotterdam in the Netherlands.

Three project dissemination workshops were then held at each of the case study ports during September 2012 (Sydney, Port Kembla, and Gladstone). These presented the draft findings and deliverables from each of the work packages to the port authorities and provided a platform for final feedback to each of the work packages.

6. WORK PACKAGE 1: UNDERSTANDING FUTURE RISKS

Research activity for this core work package involved the sourcing, collation, and interpretation of climate and non-climate data to inform the assessment activity for functional and workforce (WP2) and infrastructural (WP3) vulnerabilities; and the use of this information to scope potential adaptation options. The methodology involved:

- A literature review covering climate risks and infrastructure in the Australian context, the interpretation of climate information for risk / vulnerability assessments, and more specifically climate risk assessments as carried out for seaports internationally (found to be very few in number);
- Using current day vulnerability assessments, informed by representatives from the case study ports, to identify the critical climate variables affecting vulnerable assets and operations, including consideration of the time-lines likely to be important for maintenance and risk management;
- Close interaction with the BoM to source past and current weather / climate data for each of the case study locations in order to establish initial base-lines for the case study analysis, and to explore observed and designed extreme weather data;
- Collaborative working with the CSIRO to identify the most relevant climate models, variables and emissions scenarios to be applied, using the CSIRO's 'Climate Futures' program;
- Abstracting climate data from CSIROs OzClim portal and running it through models to provide the data in a usable format for GIS software;
- A review of grey literature to consider the impacts of non-climate drivers, and potential implications for seaports;
- An integrated assessment of the collated data to provide the necessary inputs required by the other work packages;
- Scoping adaptation options.

An integrated assessment methodology – comprising quantitative, qualitative, and participatory approaches – was extremely useful for framing the key issues and 'making sense' of the complex mix of information that needed to be considered when conducting an analysis in support of climate resilient seaports. Indeed, as stated, engagement with key experts was central to the project. Close liaison with climate information providers such as the CSIRO, the BoM, and CAWCR, was vital to the assessments carried out. Equally valued by the project team was the commitment of the case study ports. This engagement provided valuable information on stakeholder perceptions of risk and the identification and analysis of vulnerabilities from a 'bottom-up' perspective. Their input also helped to shape the research agenda as the project, and thinking, evolved.

There were six main components that acted to frame the integrated assessment of risks. These were:

1. Analysing ports as systems;
2. Considering current (and past) weather / climate data;
3. Interpreting future climate projections;
4. Reconciling climate information with research needs (risk assessment and adaptation planning for functions, workforce and infrastructure);

5. Compilation of climate information packs for each of the case study ports; and
6. Contextualising with non-climate drivers.

6.1 Analysing ports as systems

Modern-day seaports are complex systems; represented by multiple functions and assets. The schematic diagram shown in Figure 2 is not only useful for highlighting the different sub-components of the system under investigation – and the primary focus of work packages 2 and 3 – but also reinforces the importance of considering a range of different variables, beyond just sea-level rise, when identifying future climate risks.

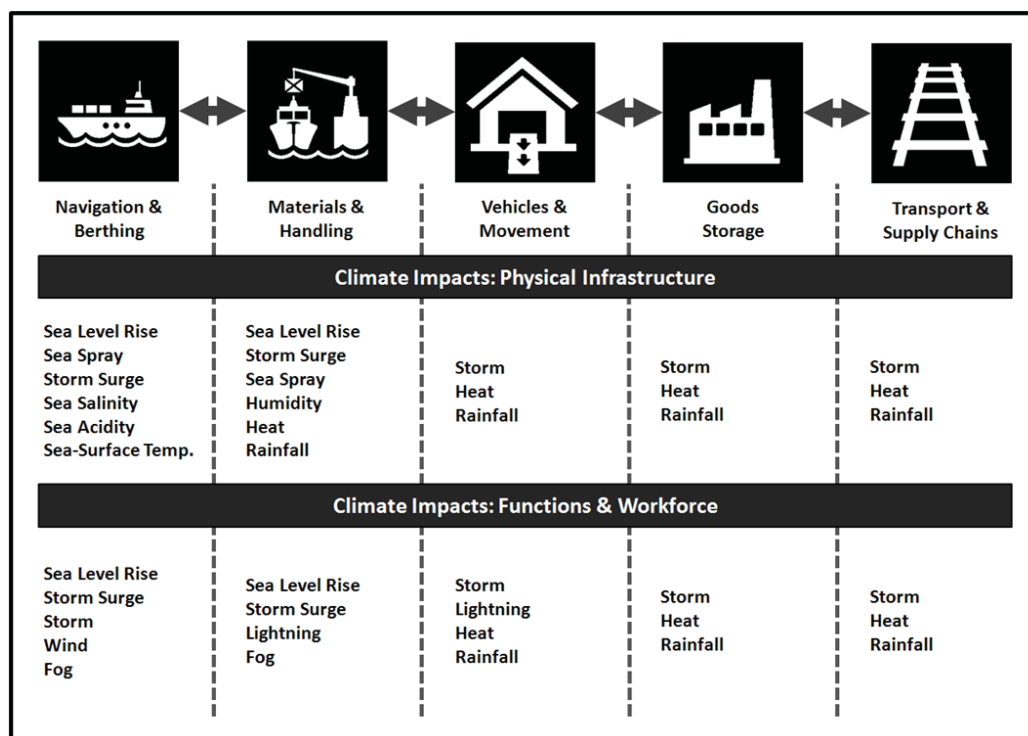


Figure 2: Potential climate impacts on different sub-components of the port system

6.2 Current (and past) climate/weather data and extreme events

The majority of data of observed climate were sourced from the BoM website. The data either came from records for specific weather stations or else programs such as Rainfall Design (IFD analysis), the record of tropical cyclone tracks, and information on climate extremes. This information was also supplemented by some new products that the BoM are currently developing e.g. MATCHES (Maps and Tables of Climate Hazards on the Eastern Seaboard). Whilst Australia is fortunate to have a rich source of past climate data, availability in some places can be patchy and did not provide an unbroken record for all variables required by this project. For example, the closest weather station to Port Kembla, the Port Kembla Signal Station, only operated between 1950 and 1977; which neither provides a record for 30 years nor matches the climatology period 1961 to 1990, used by the BoM as a baseline (as well as being closest to the GCM baseline). Data therefore had to be sourced from an alternative,

further away, weather station. This highlights the problem of trying to maintain data consistency.

Information on extreme events was collated from multiple sources: the BoM, the Emergency Management Australia data base, and the IPCC Special Report on Extreme Events (the BoM online portal contains a significant amount of observed data; however the accurate modelling of future extreme events remains in its infancy). The Disaster Database of Emergency Management Australia also provided a range of material on past natural disasters. It proved to be an uneven source of information for the purposes of this project, but was very useful in providing a broad overview of the sorts of natural disasters that the area around the three case study ports had suffered over the last century (this contextual material was useful for stimulating debate about the impacts of extreme events). More detail is available in the full report.

Current and past climate information provided an initial base from which to explore the climate-related impacts that affect the functioning and infrastructure of seaports. A focus on existing hazards was used in workshop settings to stimulate discussion around current day vulnerabilities (particularly the impacts associated with extreme events) and any adaptation measures the ports had put in place in response to climatic stressors. This focus was underpinned by the principle of addressing risks linked to current variability and the impact of extreme events as an important building block for longer-term adaptation interventions.

6.3 Future climate data

At the outset, it was thought that access to appropriate climate data to inform the engineering and logistical analysis would be a relatively straightforward process. However, this did not turn out to be the case. The project's 'journey' of matching available future climate information to end user requirements, and understanding and interpreting the processed data whilst dealing with the inherent uncertainties involved, formed a key part of the learning process for all those involved. These learnings, and knowledge gained about translating climate data for engineering and logistics applications, represent an important outcome from the project.

In the initial stages of the research activity, 'off the shelf' scenarios produced by the CSIRO were used to inform preliminary discussions regarding asset and operational vulnerability to climate-related variables for each of the ports. These are based on the latest published modelling work as showcased by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007); informed by the scenarios generated by the CSIRO and BoM (CSIRO, 2007). This coarse-level data provided the early evidence to inform discussions of vulnerability amongst the different work package teams.

More detailed climate projections were then sourced for the project from the CSIRO. The collation of data involved two important procedures: firstly, models and model data had to be selected in a consistent manner; and secondly, scenario data from these different models then had to be generated for each of the port case studies (with output collated into individual climate information packs). Ensuring internal consistency in the application of the climate data used across the project was critical to the analysis. Issues were brought to light when applying a hotter / drier future scenario to the Port of Sydney (discussed in the early Sydney workshop) which contradicted State-level guidance which considers a potentially wetter future, particularly in spring and summer months. Dealing with the inherent uncertainty of the climate science proved to be a significant challenge.

There are a multitude of global climate models (GCMs) that can be applied to the Australian context, and selecting which of these to use in the project was a complex process. As highlighted by Clarke, Whetten and Hennessy (2011) there are currently projections from up to 24 GCMs, up to six emission scenarios, and around a dozen climate variables; potentially resulting in many complex permutations. To address this complexity, and achieve internal consistency across the case study analysis, the project team was guided by the 'Climate Futures' methodological framework; a recent initiative by the CSIRO to improve the 'fit' between the complex array of GCMs that exist and the specific information requirements of different end-users. From the experience of the project, this framework is highly recommended for similar Australian studies which require scenarios that are tailored to the needs of specific applications (reducing complexity by allowing users to select a smaller sub-set of climate models which are representative of different futures).

"The novel feature in Climate Futures is the ability to assess the likelihood of combined changes in two climate variables. It is then easy to identify the full range of possibilities including the 'Most Likely', 'Best Case' or 'Worst Case' futures". (Hennessy et al, 2012)

The rationale underpinning the choice of models used in the project was to not only investigate the 'most likely' future i.e. the future climate that most of the models project, but also some of the other possible futures that may occur. The Climate Futures framework enabled a suite of models to be run that were representative of a range of possibilities (most likely, hot/dry, and cool/wet), and also ensured that there was consistency across the case study analyses. This gives the results as much robustness as possible when considering uncertain future changes (representing a more comprehensive framing of climate risks).

Complexities associated with the modelling can also be seen in the way the climate models express different climate futures for each of the case study seaports (Table 1). Although the same 3 models were used for all seaports, the model that was in the 'most likely' category for Sydney was a different model from that in the 'most likely' category for Gladstone. This not only highlights the challenges of bridging the gap between the climate modelling and adaptation communities (and how best to make sense of the complexities and contemporary limitations of climate science by non-modelling experts), but also brings home in more basic terms the sheer size and climatic complexity of the Australian continent. It should be stressed however, that the use of different models for the ports of Sydney and Gladstone does not prevent comparisons; rather the different models ensure that a full range of results is provided and thus comparisons can be made in the context of a comprehensive range of possible futures.

Table 1: Models used to represent different climate futures for the case study ports

Climate Future	Sydney/ Kembla	Gladstone
Most likely	Model MRI2.3.2	Model CSIRO Mk 3.5
Hotter drier	Model CSIRO Mk 3.5	Model MRI2.3.2
Cooler wetter	MIROC3.2-Medres	MIROC3.2-Medres
Warmer wetter	MIROC3.2-Hires	MIROC3.2-Hires

A mix of other uncertainties introduced further complexity to the research activity. These ranged from contradictions in how different organisations deal with model selection, inconsistencies between jurisdictions and organisations (including between data providers), the fact that not all GCMs incorporate the same variables (e.g. in order to gain access to salinity data a 4th model MIROC3.2-Hires had to be introduced), and differences in how climate data is expressed (notably, States differ in the dissemination formats they use). Further detail on these issues is available in the WP1 full report.

Other modelling issues specific to this work package are also worthy of note. The first relates to the choice of the emissions scenario. Whilst the initial intention was to use the 'low' SRES B1 scenario this was replaced by SRES A1B (a 'medium' scenario); considered more representative given current trends in emissions (the world is currently tracking according to a high scenario). For the purposes of the project, SRES A1FI was used as the 'high' emissions scenario, as this scenario matches closely the current rate of observed emissions) however it needs to be recognised that this particular scenario was introduced in the IPCC 4th Assessment Report to portray an 'exaggerated' case and as a consequence less data is available for it than the others. [The IPCC will introduce new climate scenario data in different formats than before in their forthcoming 5th Assessment Report].

Future projections of extreme events are difficult to extract from GCMs with any confidence. As noted by the IPCC report on climate extremes (IPCC, 2012: 11):

“Projected changes in climate extremes under different emissions scenarios generally do not strongly diverge in the coming two to three decades, but these signals are relatively small compared to natural climate variability over this time frame. Even the sign of projected changes in some climate extremes over this time frame is uncertain. For projected changes by the end of the 21st century, either model uncertainty or uncertainties associated with emissions scenarios used becomes dominant, depending on the extreme”.

The generation of climate scenarios based on each of the representative models was done through the on-line OzClim tool (<http://www.csiro.au/ozclim/home.do>); a publicly accessible tool designed to allow end users to generate and explore scenarios up to 2100 (the case study of Gladstone is shown in Figure 3). However, even with the support of such tools, scenario generation can be a complex and time-consuming process.

Data from other sources

Some of the required variables needed to be collated from other sources. This included information on sea level rise. The project used a combination of research findings to inform the assessments, including research on projected sea level rise (Hunter, 2010) and the information made available through Geoscience Australia's 'Oz Coasts Australia' online coastal portal; as well as the regionally distributed sea level rise projections which are available through the CSIRO Marine and Atmospheric Research (CMAR) website. This latter data source was used to populate the climate packs produced for each of the case study ports.

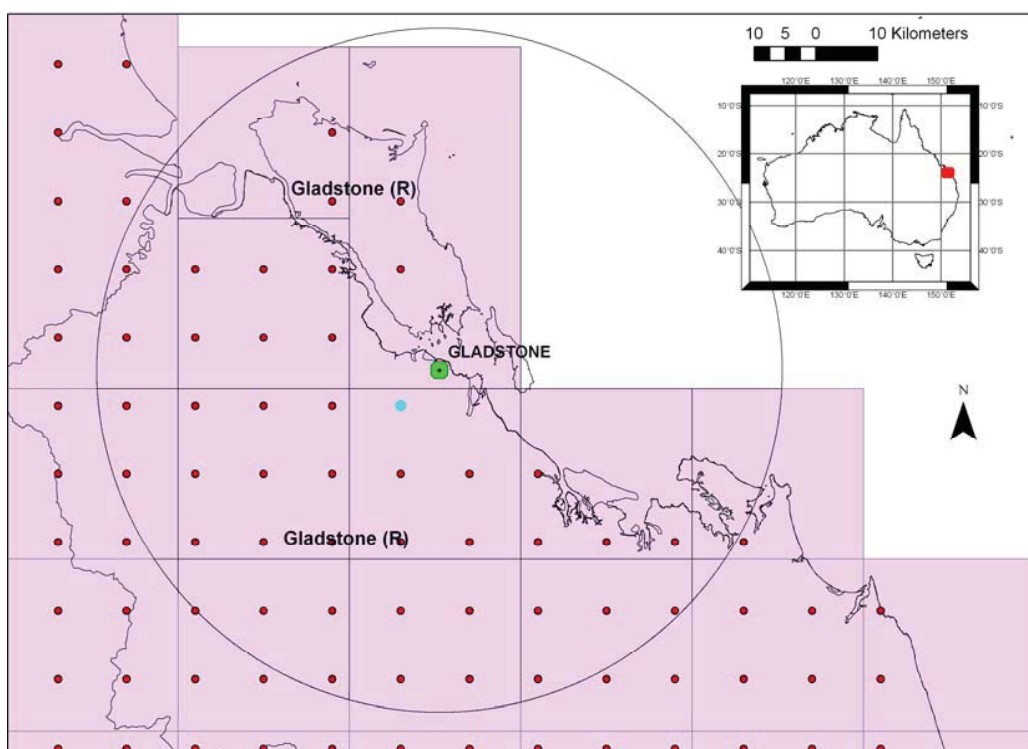


Figure 3: Gladstone. Ozclim grid cells: 1° Buffer (0.5° radius)

6.4 Reconciling climate information with research / end-user needs

WP2 required data on weather-related extreme events as this was identified to have the largest impact on the efficient operation of the seaports (Table 2 combines the initial climate information ‘wishlist’ for both work packages). Due to the difficulties of predicting actual port operations beyond a relatively short time frame, the analysis of functional vulnerability looked primarily at the occurrence of extreme weather events for 2030. Climate variables of greatest importance for this work package included extreme rainfall, temperature, fog, hail, storms and wind. A further impediment to analysing the risks from climate extremes was that the port operators engaged with did not have a precise definition for many of the thresholds affecting operations; rather they used local working knowledge and experience to identify thresholds that would invoke interventions – such as stopping work. As an example, cranes have a clearly defined wind speed threshold beyond which they are legally required to stop work (due to OH&S and engineering requirements), however when dealing with fog the accepted wisdom is that work will stop once an identified landmark can no longer be seen clearly. Thresholds for port operations are therefore subject to different formal and informal rules.

Table 2: Climate variables affecting port assets and functions

Material	Mechanism	Climate parameters
WP2		
Pavement	Loss of seal	Temperature (maximum seasonal) Rainfall (extreme)
Navigation and berthing	Delays	Extreme: temperature, rain, humidity, wind
Bulk un/loading	Delays	Extreme – temperature , rain, humidity, wind
Container un/loading	Delays	Extreme – temperature, rain, humidity, wind
Rolling cargo un/loading	Delays	Extreme – temperature, rain, humidity, wind
Yard movement and stacking	Delays	Extreme – temperature, rain, humidity, wind
Road transfer	Delays	Extreme – temperature, rain, humidity, wind
Rail transfer	Delays	Extreme – temperature, rain, humidity, wind
Workforce	Loss of work hours, other	Extreme – temperature, rain, humidity, wind
WP3		
Steel	Corrosion	Rainfall (no of wet days in 1 year) Humidity (mean decade + extreme) Temperature (mean annual) Salinity (mean decade) Wind (mean decade)
	Fatigue	Wind (mean decade)
	Fracture	Wind (extreme)
Concrete	Erosion (salt-scaling)	Salinity (mean decade) Rainfall (no of dry days in 1 year) Temperature (mean annual) Humidity (mean decade) Wind (mean decade)
	Corrosion of steel rebars (chloride ingress)	Temperature (mean annual) Rainfall (3-day wet/dry period) Wind (mean decade) Salinity (mean decade)
	Corrosion of steel rebars (carbonation)	Temperature (mean annual) Rainfall (no of wet days in 1 year)
Timber	Weather Deterioration	Temperature (mean annual) Humidity (mean decade) Rainfall (no of dry days in 1 year + distribution) Wind (mean decade) Salinity (mean decade)
	Separation of cracks	Temperature (mean annual) Humidity (mean decade) Rainfall (no of dry days in 1 year + distribution) Wind (mean decade) Salinity (mean decade)
	Marine borer attack	Temperature (mean annual) Humidity (mean decade) Rainfall (no of wet days in 1 year) Wind (mean decade)

Given the focus on deterioration of port infrastructure assets, the engineering component (WP3) required data that related to longer term changes, usually expressed as averages (i.e. annual or seasonal). The initial climate variables identified were: temperature, rainfall, humidity, wind speed (and direction); as well as patterns related to these variables such as the number of consecutive days with no rainfall, or the number of wet days in one year. The group also requested information related to changes in sea surface temperature, salinity, and sea-level rise to 2100.

However, over the course of the project, the engineering team needed to refine their understanding of what data was available from the GCM models and what additional data was necessary to model the three materials under investigation – concrete, steel, and timber. For example, temperature, humidity and the relationship between days of rain and dry days are important drivers for the deterioration of concrete. The next step was then to define how these variables were expressed: as annual or seasonal data, as averages or maximum values, etc. It was found that some of the required data, e.g. the possible future number of consecutive days with rain, was beyond the current capability of the climate models. In other instances, although available, the data were not easily accessible in the formats needed (acidity data are modelled, though the conversion of pH to an engineering expression was overly problematic). Reconciling climate data with their modelling needs was therefore an iterative process and by necessity, the engineering team had to simplify some of the inputs to the deterioration models and manage the inputs that were not available by inserting 'best guess' estimations and assumptions. Thus, over the life of the project, the engineers had to continually refine their modelling efforts to account for information that could be readily accessed.

6.5 Non-climate drivers

Climate change is only one of the many drivers affecting the functioning of ports and any risk assessment therefore needs to contextualise potential climate impacts with other important non-climate drivers. To achieve this, the project drew on key national and sectoral documentation to frame and explore the non-climate drivers that are likely to have most impact on seaports in the near to medium term. The variables considered were: demography, economy, technology, institutions, and supply chains. Key drivers for ports are likely to be significant domestic population growth (container) and a continuation of the large export trade (particularly coal and iron ore) to China and other fast developing Asian countries (bulk). Volatility in markets, for example increasing climate change impacts on agriculture both domestically and internationally, will also need to be factored into forward planning. Port planning needs to integrate land use, freight transport and environmental issues with consideration of multi-level governance perspectives at port, local, state and national levels (see WP1 full report for more detail on each of the non-climate drivers).

Integrating climate and non-climate scenarios is difficult mainly as a result of their respective time horizons. For example, climate scenarios are typically modelled through to 2100 (with impacts becoming more significant in the second half of the century), in contrast to changes in socio-economic variables which are difficult to forecast accurately beyond a much shorter time period. The IPCC (2007) note that "over the course of 50-100 years, even the most basic scenario drivers, such as population and aggregate economic activity, are highly uncertain" and suggest that a timeline of "20 years may be more appropriate, reflecting the immediate needs of decision-makers".

7. WORK PACKAGE 2: FUNCTIONAL RESILIENCE OF THE PORT ENVIRONS

Research carried out for work package 2 focused its attention on port operations, considering both functional assets and the workforce that operate them. The analysis was structured according to three main domains: 1) building an asset register and assessing the vulnerability of functional assets within the port environment, 2) simulating the possible impact of extreme events on port operations, and 3) analysing the adaptive capacity of the work force, with subsequent results then used to inform training guidance. Whilst the original intention was to consider adaptation options within this discrete work package it proved more logical, as the project progressed, to make this a project-wide effort that would ultimately inform comprehensive adaptation decision-support guidance for seaports. As such, WP2 and the adaptation guidance document are available as separate project reports.

As noted earlier in this synthesis, weather-related extreme events have the greatest impact on the efficient operation of the seaports. Thus, the scope of the research activity on functional resilience was heavily influenced by the availability of information and data. Key constraints encountered included: the difficulties associated with predicting actual port operations beyond a relatively short time frame, the current uncertainties associated with modelling future extreme events, the lack of formal quantitative thresholds for climate variables affecting some port operations, and finally, restricted access to freight flow data. As a result, the assessment of vulnerability relied primarily on assessing current day vulnerability to extreme events (informed by port personnel and records), with the simulation of impacts on operations within the immediate port environment using extremes data that were available for 2030.

7.1 Asset register, vulnerability assessment, and visualisation

A comprehensive Geographic Information System (GIS) assets database was developed for the port precinct of Port Kembla Port Corporation. This was considered an appropriate exemplar port given that it is relatively discrete, handles a diversity of cargoes, and as such carries out a wide-range of logistics procedures. The GIS assets database identified and mapped the core operational assets for sea, land, and sea-land interfaces which formed the basis of the analysis of logistics operations; as well as providing data for the 3D visualisation modelling of vulnerable assets to sea level rise (a GIS has the advantage of providing a visual asset management tool, significant in spatially dependent businesses such as port logistics operations).

Assets captured in the register were attributed according to three sets of characteristics. These include: 1) asset-related attributes, 2) environment-related attributes, and, 3) maintenance related attributes. This classification framework was demonstrated to be effective in capturing the diversity of assets in conjunction with their broad characteristics. The assets database also contains information on ownership, quantity and types of assets for the purpose of enabling various stakeholders to assess their vulnerability to climatic events, and has been structured to store maintenance and utilisation related records to assist in asset valuation, asset life-cycle, and performance assessment.

This work package domain also presented a GIS-based spatial methodology, drawing on high resolution LiDAR and aerial imagery databases (for the Port Kembla case study), which provided 2D and 3D visualisation of the potential impacts of a rise in sea-level. However, whilst proving potentially of value in the communication of potential climate impacts, such an approach is resource intensive and is a prototype best suited

to visualising risks that have been identified and prioritised rather than in the scoping stages of an assessment.

The register of core operational assets, together with the GIS-based mapping and input from port stakeholders, then formed the basis for the development of vulnerability matrices for each of the case study ports. The formats were designed in a manner that permits application in any port context and can be populated by the personnel of individual ports. This bottom-up exercise, ranking the importance of vulnerabilities using expert knowledge, was also found to be a valuable way of collating relevant information on the local impacts and thresholds of extreme events. In Gladstone, cyclones were of greatest concern, primarily affecting assets at sea and at the sea-land interface. Port Kembla noted high wind speeds and storm surge as problematic, with cranes particularly affected. Sydney identified a range of different hazards – intense rainfall, heat waves, storm surge and wind – with most concerns raised about land assets. Further details are contained in the full report.

7.2 Simulating the possible impact of extreme events on port operations

The simulation model developed for this domain assessed intra-port logistics operations and assets when perturbed by the impact of extreme events. This exercise involved building a logistics workflow system that mimicked the land side operations of container (TEU) handling and movements including unloading, loading, and transshipment / intermodal operations. It then introduced the possible impact of climate-related disruptions to these container terminal operations.

Sydney Port Corporation, along with one particular terminal within the Sydney Port Corporation precinct, was selected as a test case to build a Container Terminal Operation Simulator (CTOS). The model was developed in order to mimic the container movement workflow of a single terminal, though the modelling methodology has been designed to be replicable and transferable to other terminals and ports. A single terminal was chosen in order that a finer scale of detail could be captured and modelled; producing a closer to real-life outcome of climate impacts on operations.

The simulation enabled a systematic assessment of various ‘what if’ scenarios associated with extreme weather events that are of most concern to port operations (informed by terminal operators), under future climate scenarios. The outcomes were a set of Key Performance Indicators (KPIs) that allowed a comparison of the level of operational performance (e.g. crane rates, straddle productivity, truck queue length, yard utilisation) to be made under various scenarios. The CTOS emulated the impact on the capacity of different operational assets, and measures the variation in performance levels and the overall throughput within the container handling process. The CTOS has been designed and coded in a manner that permits its modification such that it can be applied to other port contexts.

The model uses agent based modelling and simulation (ABMS), which allows individual actors/nodes in a process to be independently encoded with operational rules in order to observe the collective behaviour. ABMS allows the logistics performance of operational assets to be individually and collectively modelled. By encoding the operational rules of individual operational assets (i.e. nodes in the process workflow), the likely impact of climate events on the business process flow when the performance of different operational asset nodes reduce to a sub-optimum level can be measured and compared. A high level design of the various agents in the system and their interactions are shown in Figure 4.

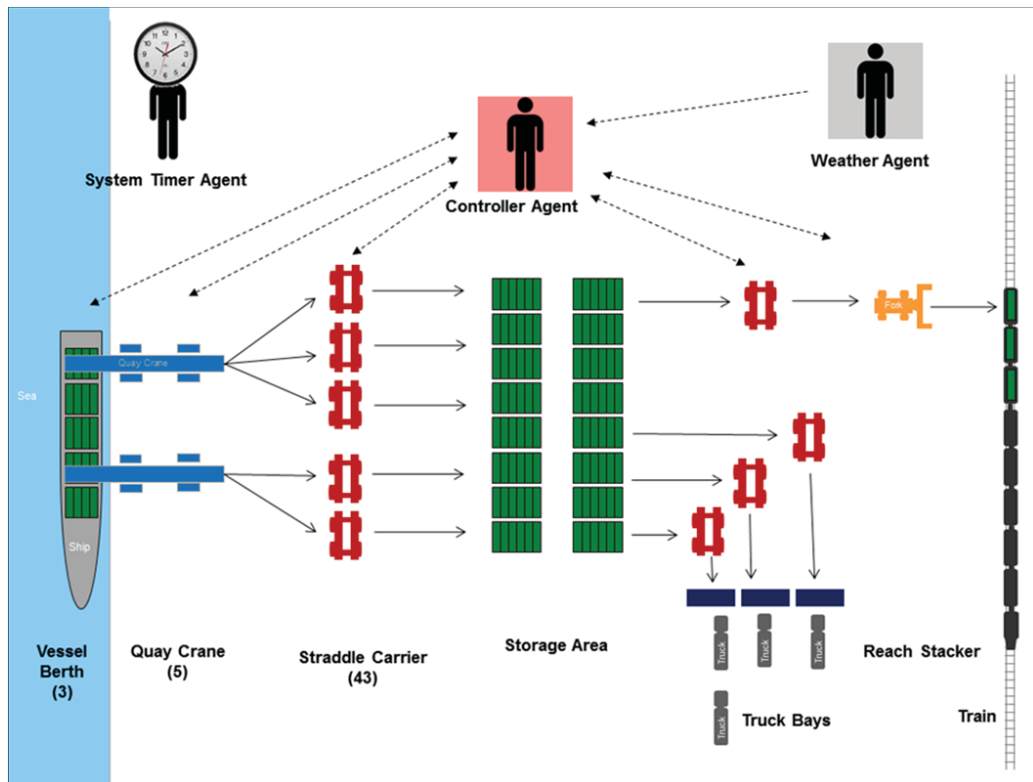


Figure 4: System agents and their interaction

The simulation model analysing the container flow patterns addressed the following research questions:

- What is the likely impact of a range of extreme weather events on the total number of containers handled at a container terminal over a 24 hour period (and how will this be affected by changes in intensity and / or duration of events)?
- What is the average productivity loss – defined in terms of average time required to handle a container – of different operational assets under different climate change scenarios (represented by the three different climate ‘futures’)?
- What is the likely impact on the performance of key operations such as ship turnaround time and truck service lead time given projected growth in container numbers and the likely increase in intensity of future extreme events?

The outcomes of this simulation model generated a set of results that allowed a comparison of the level of operational performance when impacted by an extreme event. After discussion with terminal operators, it was learnt that almost all climate events tend to impact on agents and operations in a “stop work” manner meaning that when conditions are extreme, all components of the workflow cease. Work resumes as soon as conditions improve. Any time in productivity that is lost during periods of stoppage is made up in later shifts. Information on the weather variables of most concern was sourced from the terminal operators; including impact on the productivity of the container movement workflow, particularly at each node, and the connecting processes between each node. It was found that climate variables of most concern to tenants (in order of most to least important) include rain, wind, heat, fog, flash floods (Table 2).

Table 2: Weather variables of most concern to port tenants and the impacts on the workflow

Weather variable	Impact on workflow
Rain	<ul style="list-style-type: none"> • There is no formal quantity of rainfall to determine whether employees should stop work. • When work stoppage occurs due to rain, all components of the workflow stop.
Wind	<ul style="list-style-type: none"> • Cranes and straddle carriers are equipped with wind alarms. Once a wind alarm goes off, operators must cease work. Once the alarm stops, operations resume. • Cranes stop work at 70km/hour wind strength. • Straddles stop work at 90 km/hour wind strength.
Heat	<ul style="list-style-type: none"> • Heat policy – 36 degrees, breaks become longer. At 38 degrees, work ceases. • Work continues as soon as the temperature drops.
Fog	<ul style="list-style-type: none"> • Informal policy – if the cranes on the ship can't be seen from operator's office block building then it's too foggy to work
Floods	<ul style="list-style-type: none"> • No overall flooding at the terminal because of effective drainage systems. However there is isolated flooding where drainage cannot cope (source of flooding is rain).

CTOS has an agile design structure, which is adaptive to fit to user's requirements in creating realistic 'what if' scenarios, to mimic the impact of extreme weather events on port logistics operations. Model runs considered five scenarios (shown in Table 3), including a baseline for comparison, the impacts of high temperature, heavy rain, high wind and extensive flooding impacting the port precinct over a 5-6 hour duration in a single day. 2030 scenario data for high temperature days were also incorporated.

Table 3: Modelling scenarios

Scenario name	Description
<i>Scenario 1</i>	Baseline (no impact)
<i>Scenario 2</i>	High temperature / heatwave for six hours per day
<i>Scenario 3</i>	High rainfall / flash flooding for six hours per day
<i>Scenario 4</i>	High wind / cyclone for six hours per day
<i>Scenario 5</i>	Flooding of port area affecting straddle operations for five hours

The results of the simulation showed that while the impact due to these events were relatively insignificant on the container-related operations, rain and high wind made the most impact while flooding in the yard area hindered the operations of the straddle carriers and led to backlog queues being created for trucks. Furthermore, using annual hot days occurring at present and projected for 2030, the modelled current impact is a loss of 184 containers per year at present and 241 containers per year based on the projected hot days in 2030 (less than 0.01% of the annual container trade of the port).

7.3 Port workforce adaptive capacity

The final domain of work package 2 considered the human dimension; specifically the adaptive capacity of the workforce. Adaptive capacity was investigated through semi-structured interviews with staff conducted between July and September 2012. The different case study ports are characterised by different management structures, locations and operational characteristics; thus offering the opportunity for inferring the findings to a broader range of Australian ports. The interviews were conducted mainly with staff from the operations, human resources, and environment departments (or equivalent departments) of the ports. Through open-ended questions, respondents were invited to explain and discuss climate change and port operations with reference to: 1) specific experiences of extreme weather events at their respective ports, and how they were addressed, 2) their perspective on future changes to the climate and possible implications for port operations, 3) existing procedures to deal with extreme weather conditions, and 4) their views on the vulnerability of their ports to weather disruptions presently and in the future. With respect to existing procedures, interviews explored whether they were documented or rather based on organisational and individual knowledge.

Analysis of adaptive capacity was then framed by three key elements: the knowledge / skill of the members of the workforce to cope with extreme events, the implied organisational customs / norms towards climate change, and the organisational management systems which address the impacts of extreme weather (Figure 5).

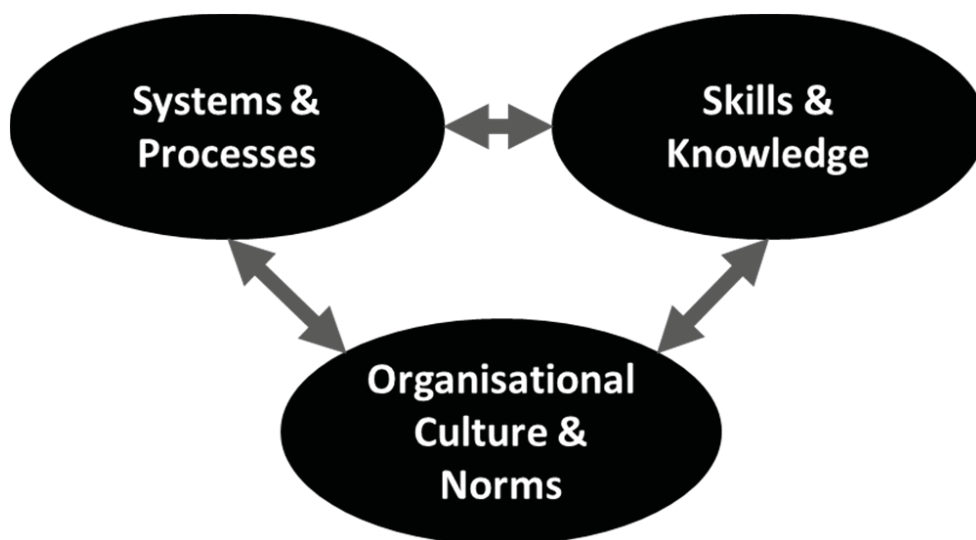


Figure 5: Elements of adaptive capacity

Systems and processes: All the ports involved in the study operate quality and environmental management systems (EMS), occupational health and safety (OHS), as well as emergency management and recovery and risk management systems. These have all influenced the incremental introduction of measures that can be considered to have improved resilience to current day climate-related impacts. One option, raised by one of the port personnel interviewed, to further strengthen resilience would be to revisit the thresholds determined in enterprise bargaining and OHS systems, such as wind speeds and heat thresholds, to account for climate change.

Skills and knowledge: The environment staff at all three ports (or those staff with specific environment responsibilities, such as environment planning or monitoring and compliance), clearly had an understanding of climate change and its potential impacts on their respective port environs. However, they themselves did not have the technical knowledge and skills needed to assess the resilience of infrastructure assets or address shipping constraints that particular weather thresholds may impose etc. This suggests that the adaptive capacity of an organization can be enhanced by greater sharing of knowledge and expertise. Most port staff interviewed exhibited a fairly confident understanding of sea level rise implications for their region. An important aspect of individual knowledge and skill acquisition is access to information. However, as this project has found, future climate data for local areas can be difficult to both source and interpret. One option for improving knowledge and skills was considered to be through professional development opportunities (though these will differ according to different professions and trades).

Organisational culture and norms: The organisational culture, as it relates to climate change adaptation, is strongly influenced by the leadership team, their understanding of climate change and its potential impacts, and ultimately their willingness to adapt. Suggestions for promoting a “climate change culture” emerged during the engagement process including developing a business case that outlined what the cost of adaptation action would be, versus inaction to respond.

Key findings arising from the evaluation of adaptive capacity were that the greatest opportunities for training around climate change issues in ports are likely to be through:

- Executive risk and climate awareness training specifically targeting executive level management at ports, delivered through a recognised and respected industry organisation such as Ports Australia.
- Strategic futures training, which includes climate considerations, targeting executive, senior and middle managers involved in port planning. Scenario analysis is one of the tools often employed as part of climate adaptation planning.
- Training on how to adapt existing organisational management systems to incorporate climate considerations.
- Climate risk management training would help ports build specific skills and knowledge in this area, greatly improving their adaptive capacity.
- General climate risk awareness training would provide more generic climate awareness training for management, administrative and frontline staff.
- Accessing and interpreting relevant climate information was identified as a gap through the project. This would involve working with specialist port personnel to help them identify, source and interpret the data.

8. WORK PACKAGE 3: STRUCTURAL RESILIENCE OF CORE PORT INFRASTRUCTURE

The research activity for work package 3 concentrated on the longer-term deterioration rates of core port infrastructural assets under a changing climate. Up front, it is important to note that the modelling did not examine the impacts of future extreme weather events (such as extremes in rainfall and temperature, or changing flood frequencies) which will also impact on structural condition and operation; rather it focuses on longer-term deterioration (itself a challenging modelling task). The research consisted of six discrete tasks: the identification of structural assets, interpretation of climate data for use in the engineering model, long-term deterioration modelling, the generation of resilience matrices, development of a methodology for life cycle costing, and finally the production of an on-line software tool for use by port engineers. Full details are contained in the work package report.

8.1 Asset identification and deterioration modelling

There are five distinct zones that affect structures in water (see Figure 6). These zones are atmospheric zone, splash zone, tidal zone, zone of continuous immersion, and seabed zone. The atmospheric zone tends to contain some amount of salt, which increases the rate of atmospheric corrosion of marine structure with metal and deterioration of concrete over that of land structure materials. In timber structural components above the splash zone, fresh water may collect and stagnate, initiating rot. The splash zone constitutes an area from the high water level to the upper levels attained by spray. This zone is subjected to intermittent wetting and drying as waves run up or break on the structure. The tidal zone is the usual range between high and low levels which is periodically immersed. Below low tide level to the seabed the structure is continuously immersed and this is typically a zone of moderate to light attack on steel and concrete but not timber. Below the seabed, the structure's elements are buried and are relatively well protected as the lack of oxygen prohibits oxidation and the existence of most organisms.

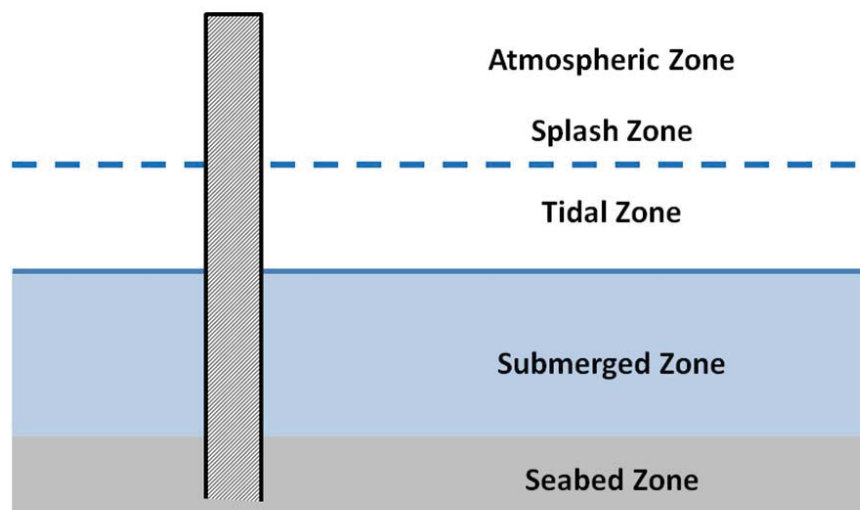


Figure 6: Zones of structural deterioration in the marine environment

The first stage of the vulnerability assessment involved the identification and categorisation of port assets. To provide a framework for deterioration assessment, the physical structure subgroups were aggregated to 3 large categories by type (materials and structure) and in deterioration behaviour. The three aggregated groups were concrete, steel and timber structures. Case study analyses was then conducted using port asset registers and 'ground-truthing' through site visits, and included consideration of the type of use and location (seaside, landside and transport) to assess potential vulnerabilities to different climate variables. Vulnerability is influenced by a range of variables; including: structure type, type of material, location, elevation, and loading.

With the necessary baseline data in place, deterioration models were developed to simulate the effect of future climate change on key port infrastructure. Currently, there is a lack of models that include the impacts of a changing climate when predicting deterioration as a function of time. To address this deficiency, numerical models involving simultaneous transient diffusion and long term deterioration reactions for various construction materials were developed. These were derived from existing models and include the effects of variations in climate 'properties' such as humidity, temperature, atmospheric CO₂ concentrations and chemical reaction rates, as a function of time. Considerable effort was needed to identify the most appropriate climatic inputs for the models. Climate data were drawn from both historical weather records and future climate projections in order to refine existing deterioration models by incorporating climate data into modelling runs. This enabled changes to deterioration rates of different materials to be assessed (climate parameters which would affect long term performance of the port infrastructure were identified as sea-level rise, water table, temperature, rainfall/runoff, wave, wind, salinity and humidity).

A probabilistic approach using material and dimensional data (provided by the port authorities) was used to simulate runs on a yearly increment from the baseline year up to 2070. Four deterioration models were developed to assess the performance of structural elements: carbonation and chloride ingress models for concrete, marine borer attack for timber, and corrosion of steel. These models were written in Microsoft Excel and Visual Basic for Application and later integrated into the software tool.

8.2 Modelling results

Table 5 provides a summary of the outputs from these models. The modelling approach that was used has provided quantitative projections of damage probability to port infrastructure taking into account the variability of material type, design considerations, and changing exposure and loading due to a changing climate. The deterioration predictions from the models are in a quantified form, and are therefore suitable for risk management, cost-optimised design, development of good practice manuals, and establishing a 'proof of concept' durability design guide that accounts for a changing climate.

Table 5: Summary of material model outputs

Material models	Climate variables	Outputs	Outcomes
Concrete	<ul style="list-style-type: none"> • Surface temperatures • Relative humidity • pH level • Tidal range • Carbon dioxide concentration 	<ul style="list-style-type: none"> • Carbonation- induced corrosion initiation probability • Carbonation depth • Chloride ingress-induced corrosion initiation probability • Rebar loss 	<ul style="list-style-type: none"> • Prediction of service life (risk management) • Improved durability (maintenance regime) • Socio-economic analysis (design optimisation)
Timber	<ul style="list-style-type: none"> • Surface temperature • Salinity • Sea temperature • Tidal range 	<ul style="list-style-type: none"> • Probability of attack • Marine borer attack depth • Residual remaining cross-section 	
Steel	<ul style="list-style-type: none"> • Surface temperature • Relative humidity • pH level • Tidal range 	<ul style="list-style-type: none"> • Probability of corrosion • Reduction in cross-section due to corrosion 	

Whilst the modelling provides a valuable resource for forecasting material degradation of port assets under changing climatic conditions, an important caveat relates to the need for reliable climate data to ensure modelling robustness. As found by the project, there are some key limitations to the climate change data. A prime example is that the scenarios produced by ‘climate futures’ only generates projections up to 2070, hence restricting an assessment of climate change impacts on port structures over a longer service life (important for long-lived structures). The high levels of uncertainty inherent in climate change modelling can also be problematic when combining these data with the less flexible nature of the engineering models. Where gaps existed in climate parameters, this has been addressed by making assumptions. Also, some records of legacy structures were not available for the case study ports due to poor record keeping practices and therefore assumptions have been made based on engineering standards pertinent to the time-period of construction. However, the approach taken is believed to provide the most informed assumptions given the available data. Overall, the deterioration models that have been developed constitute a valuable resource for port authorities – providing decision-makers with advanced information about the impacts of a changing climate and the implications for a port’s long-term capabilities and resources.

Key analytical outcomes relating to typical structural assets indicated the following:

- Carbonation-induced corrosion in concrete is the deterioration that is most aggravated by climate change. The intervention time required could be as early as 16 years compared to the current climate.
- Chloride induced corrosion is significantly affected by the surface temperatures. The resilience of concrete materials decreases from high to low at 2070.
- The splash and tidal zones are usually the most vulnerable and are characterised by cracking and spalling of concrete due to wetting and drying and corrosion of reinforcements. These zones will alter over time due to sea level rise and increased storm surge as a result of climate change.

- Marine timber attack is affected by sea surface salinity. Under 2050 medium, 2070 medium and high emissions, this effect is projected to no longer influence the probability of borer attack; however the depth of the attack on timber is still significantly affected.
- The resilience of steel structures is projected to increase over time with relative humidity identified as the most influential climate variable.

8.3 Decision support tools

In support of more informed decision-making the project has developed a design and maintenance cost management tool to optimise maintenance sequence and determine the effectiveness of maintenance option in the form of net present value return. The life cycle costing comparison indicated that climate change will have a significant effect on the whole of life cost of port infrastructure.

The deterioration model has also been integrated into a software tool for end users (in this case the case study ports); to be made available on-line. The tool (Figure 7 provides a screenshot of the interface, Figure 8 a results page) captures user input via a sequence of web forms and uses the Microsoft Excel based projection model for executing the mathematical formulae. This approach of integrating the Microsoft Excel based model allows new information to be easily added to the online tool by replacing the relevant Excel files, without the need to make complex programming changes.

The screenshot shows a web interface for entering climate data. At the top is a dark blue banner with the text 'CLIMATE DATA' in white. Below this is a light blue rectangular form. Inside the form, there are four rows, each with a label on the left and a dropdown menu on the right. The labels are 'Location', 'Carbon Emission Scenario', 'Climate Futures Model', and 'Year'. Each dropdown menu contains the text 'Please Select' and a small downward-pointing arrow icon. To the right of each dropdown menu is a small question mark icon. At the bottom right of the form is a blue button with the text 'NEXT' in white.

Figure 7: Screenshot of the software tool interface



Figure 8: Example of a results page

9. ADAPTATION GUIDELINES

Adaptation is defined by the Australian Government (Australian Greenhouse Office, 2006) as “actions in response to actual or projected climate change and impacts that lead to a reduction in risks or realisation of benefits”. While adaptation to climate hazards and risks can be reactive or anticipatory, it is important to note it is not an end point in itself, rather, it is an ongoing process. Several studies (UKCIP, 2011; AGIC, 2010; HM Government, 2011) have elaborated on some of the core principles that underpin effective adaptation. These, shown below, have been used to inform the development of adaptation guidelines in support of climate resilient seaports.

- Ensure executive understanding and commitment to adaptation;
- Build or secure appropriate technical capability – to undertake climate risk assessments, and to assist with implementing adaptation options, and ongoing monitoring;
- Work in partnership – climate impacts do not respect borders, working with relevant partners contributes to more effective outcomes;
- Understand risks and thresholds – ideally identified and analysed through some form of risk assessment process;
- Manage highest priority risks first, in a balanced way with non-climate risks;
- Employ adaptive management principles to cope with uncertainty – that is, iterative decision-making, incorporating feedback, and testing / updating of assumptions;
- Look for “no/low regrets” and “win-win” adaptation options – those that as well as reducing the risks of climate change impacts, help produce other benefits ;
- Avoid “maladaptation” – or actions that limit future adaptation options;
- Ensure adaptation is effective, and is reviewed regularly – reducing risks without introducing unintended effects;
- Ensure adaptation is efficient – long-term benefits outweigh the costs;
- Adaptation measures are equitable – the effects of different adaptation efforts, and the costs should be considered across different groups/sectors.

9.1 Vulnerability / risk assessment

Climate change adaptation is highly context specific, so generic adaptation actions cannot be adopted without appropriate site-specific investigation. For this reason, this research recommends port authorities undertake a location-specific climate risk assessment, building on the AS/NZS ISO 31000 Risk Management standard. It is important to note that there is not one 'correct' way to conduct climate change assessments, rather there are many approaches that could be taken (Dovers 2009; Fünfgeld and McEvoy 2011). However, risk management, as described below, is emerging as the most applicable method for assessing climate change impacts and identifying adaptation options.

All ports will generally operate a risk management system, which may or may not be aligned with the AS/NZS ISO 31000 Risk Management Standard. This standard provides a structured approach to enterprise risk management. Modifying this approach to incorporate current day vulnerabilities to extreme weather events, as well as considering future climate impacts embodied within a “hybrid” risk/ vulnerability approach would appear to be suited to ports, in that it addresses two of the key barriers

to effective climate change adaptation; that of inconsistency in planning horizons and uncertainty of future localised climate projections. It has been noted (Becker, 2011; IAPH, 2011; UKCIP, 2007) that the short organisational planning time-frame of between 5 – 15 years, does not facilitate consideration of impacts that may not materialise for 30 – 90 years. However, port infrastructure generally lasts beyond these short planning timeframes. Additionally, the uncertainty inherent in future climate projections, particularly at the downscaled local level, can lead to decision-makers deferring action on climate change until there is perceived to be more certainty in projections. Addressing current vulnerabilities, identified through a hybrid assessment framework, is put forward as one way to overcome this inertia (see Figure 9).

The assessment process consists of:

- Stage 0 – Getting started: executive support
- Stage 1 – Establish the port context
- Stage 2 – Identify current vulnerabilities and future risks
- Stage 3 – Analyse and evaluate risks
- Stage 4 – Identify and prioritise adaptation options
- Stage 5 – Monitoring and evaluation

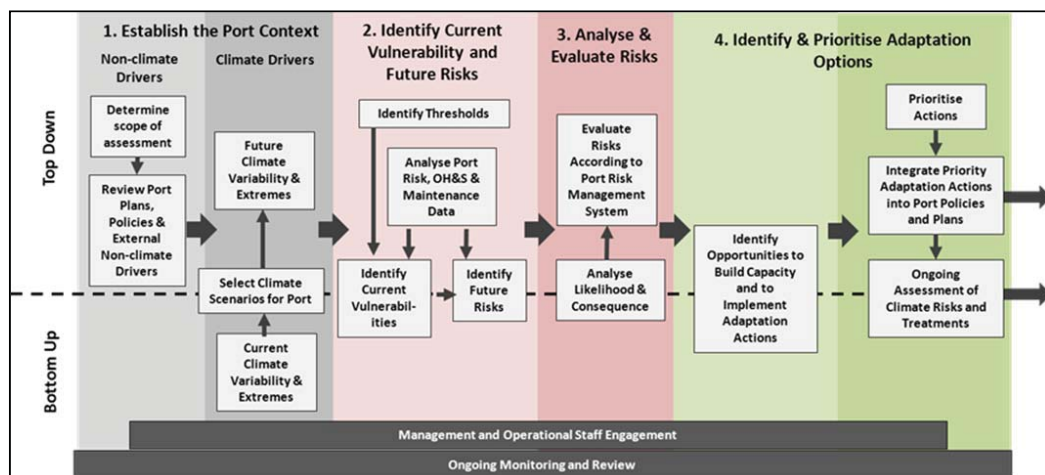


Figure 9: Hybrid vulnerability / risk assessment process for ports

9.2 Adaptation options

Implementing adaptation actions, as already noted, is highly context specific. However, through the project, several innovative adaptation actions were identified, with further opportunities to improve logistics flow, manage infrastructure lifecycles and reduce potential OHS hazards, as additional co-benefits to building climate resilience.

Building adaptive capacity to future climate change involves developing the organisational ability to respond effectively to climate change challenges. It covers such things as awareness raising, skill development, data collection and monitoring and research. Several further opportunities to build adaptive capacity were identified through the project, covering training for awareness raising and skill development; data collection and monitoring, and research.

Implementation of adaptation actions is concerned with taking practical steps to reduce vulnerability to climate risks (or develop opportunities). It includes technological, engineering change, design and maintenance, planning, insurance measures and management system change. Opportunities identified during the course of the project covering technological, engineering, design and maintenance, planning, insurance and management system change as shown in Table 6.

Table 6: Adaptation opportunities

Action area	Adaptation Action
Technological	As extreme weather events become more frequent, more targeted investment in technology that expands the operating boundaries of equipment, for example, cranes that safely operate under stronger wind gusts.
	To address increased temperatures, alter refrigerated storage specifications to meet demands of temperature changes and seek less energy intensive alternatives.
	Onsite renewable and low emission energy for a range of functions, to avoid risks associated with power disruption, the increased cost of energy and environmental legislative requirements. Some of this is already happening, for example, fuel cells to power mobile logistics elements and to cool refrigerated cargo, and photovoltaic cells to generate administrative building power requirements.
	Automation of logistics procedures is already being undertaken at some ports, and this process is expected to continue.
Engineering	Future procurement of assets such as gantry loaders, conveyor belts, shore cranes etc. needs to be assessed against future operating environment requirements. That is, the expected life of the equipment, and anticipated future climate it needs to operate in, needs to be considered.
	Storage facilities may need to be upgraded to accommodate more extreme events.
	Assess and upgrade drainage systems to cope with projected intense rain events (potentially work in partnership with city governments for this option).
	Ongoing hydrographical monitoring, to identify if dredging requirements need to be modified.
	More robust dust suppression systems may be required (such as covering coal stockpiles, rather than just dampening)
	Incremental growth of breakwaters as sea conditions require; alternatively, assessing whether breakwaters need to be reconfigured to deal with unpredictable swells conditions.
Design and Maintenance	Roadways in, and through the ports may need to be raised to respond to flooding issues.
	Encouraging modal shift to improve resilience by introducing elements of redundancy into the supply system; that is, removing the reliance on EITHER rail OR road, but looking at better incorporation of the two.
	Ensure climate changes are included in future design specifications, including accommodating future rainfall requirements into new building designs, incorporating sea level rise and storm surge into all port infrastructure elements.
Planning	Ensure ports have a proactive infrastructure and asset management plan that considers asset lifecycle elements, including altered materials deterioration regimes.
	Working in partnerships with city governments and supply chain logistics infrastructure providers to appropriately plan and design connected logistics hubs, resilient to the impacts of climate change relevant for the area.
Insurance	Investigate diversification of trade into climate resilient commodities.
	Some risks cannot be mitigated, and instead, the risk may need to be outsourced to a third party, through purchasing insurance. Working collaboratively with insurance providers to determine the quantitative elements of climate risk will assist ports to appropriately insure against risks they are unable to reduce.
Management systems	The range of systems that could incrementally introduce climate considerations includes environmental, OHS, emergency and risk management systems. <ul style="list-style-type: none"> - Updating policy elements across the management systems to include consideration of climate change impacts - Incorporate training on climate change, as part of ongoing system training elements - Consider appropriate strategies and metrics for the different management systems, and relevant to individual ports. - Update legal compliance elements regularly.
	Develop pandemic plans as part of the emergency preparedness and response system. This was discussed as an opportunity particularly for the more northern ports, as vector and water-borne diseases become a more likely threat.

10. IMPLICATIONS FOR POLICY, PRACTICE AND FURTHER RESEARCH

This concluding section reflects on some of the key findings that have arisen from across this wide-ranging activity, and attempts to frame these through practitioner, policy-making and scientific lenses, in support of 'enhancing the resilience of seaports to a changing climate'.

10.1 Evidence from the port case studies

This section summarises the key findings from the case study analysis and draws out some of the implications for practice in bullet point format.

- Engagement with the case studies indicated that resilience to current day climate variability is evident within the immediate port environment (at least at the level of individual organisations). This has not resulted from an explicit strategy for adaptation rather can be attributed to autonomous adaptation that has occurred primarily as a result of a combination of regulatory and operational mechanisms such as OH&S requirements, risk management strategies, and incremental changes to practice brought about by the ports experience of previous weather-related events. These existing mechanisms could be used to mainstream climate change interventions to a greater extent.
- Linked to the point above, ports already have processes in place that whilst they may not be labelled as adaptation, they none-the-less contribute to resilience. A valuable exercise would be to identify these as part of any commitment to an adaptation agenda. In addition, climatic thresholds which affect port operations should be continually revisited and adjusted where issues are identified. Indeed, ports already collect climate information of concern to them but often do not analyse this in any strategic sense. This could be more effectively collated and interpreted to better understand local trends.
- Important vulnerabilities were identified by the assessment; with the seaward-side of operations (moving and mooring, loading and unloading ships) and the supply chain hinterland (it is often disruptions to the supply chain and supporting infrastructure that will cause greatest disruption to the actual port) found to be most affected by current climate variability. Continued research is needed into the modelling of seaward variables of concern, extreme events and possible consequences, and the impact on wider supply chains.
- That said, evidence indicates that the case study ports are beginning to address some of their current vulnerabilities (e.g. working with local authorities on drainage issues, building in sea-level rise headroom, extra training for marine operations staff to be able to perform in rougher seas etc.)
- Although projecting the future impact of extreme events is problematic the uncertainty should not be seen as a barrier to planning for change. Current day vulnerability can be used as an initial platform for thinking through the impacts of future extreme events. The impacts of low probability though high consequence events should be considered by ports, and planned for. In such instances, there is a role for insurance to act as a mechanism for considering 'what if' scenarios and to compensate for unavoidable risks.

- A focus on identifying current vulnerabilities, and dovetailing with ports existing decision-making processes, can act as a building block for longer-term anticipatory action.
- As ports are operational hubs for the logistics supply chain, it is logical for ports to undertake an assessment in partnership with key logistics providers and /or local governments. This requires a coordinated approach to long-term planning of land-use, factoring in "room to move" for ports and other critical infrastructure (road/rail along the national supply chain routes).

10.2 Making sense of the climate science

There was genuine interest from the port personnel engaged with in better understanding future climate risks. However, accessing and interpreting localised climate data is complex and requires a high level of modelling expertise. Some of the main findings for practitioner, scientific and policy communities are listed below:

Practitioner

- Different assessments within the port environs required different types and formats of climate information. Improved reconciliation of information provision with end-user needs will undoubtedly improve decision-making. This requires new ways of collaborating between all those involved. More informed adaptation planning – beyond that of just seaports – will also benefit from climate information in more accessible formats.
- Uncertainty in future climate change projections should not be a barrier to adaptation planning. Assessing vulnerability to current day climate variability can be used as a platform for considering longer-term adaptation (natural variability being a key influence in the near term).
- The forthcoming IPCC 5th Assessment Report will introduce an updated set of climate data, in new formats, and it is important that Australian end-users are made familiar with this resource.
- As a consequence of the lessons learnt from this research project, follow-up activity (funded by the Australian National Data Service) is now being undertaken to design a proto-type web-based decision-support toolkit for Australian seaports that will help inform their adaptation planning.

Science / research

- Dealing with the uncertainty of climate data can be challenging. This project has developed a methodology that can be used to help guide other similar climate risk assessments. The selection of climate models was informed by the CSIRO 'Climate Futures' framework. This enabled a suite of models to be run that were representative of a range of possible futures (most likely, hot/dry, and cool/wet), and also ensured that there was consistency across the case study analyses. This is a recommended resource for other similar assessments.
- The climate information included both observed data and data for future time periods. As such, the project introduced a hybrid risk / vulnerability approach for assessing climate change. This integrated a top-down approach (climate science) with bottom-up vulnerability perspectives. Observed data was used to frame discussions of current vulnerability to extreme events, and given information constraints, was also used as a building block to consider possible future impacts. Given the influence of natural variability in the near term, such a

vulnerability approach is valuable as well as being 'fitting' with a port authority's decision-making timelines.

- The suite of tools developed for the project can assist relevant port personnel in making more climate-informed decisions. For instance, findings from the engineering model indicate that there will be marked changes in the deterioration of materials under changing climatic conditions. This will need to be factored into maintenance regimes; impacting on the balance sheet of port authorities (consideration of maintenance versus capital budgets). It is worth noting that new assets tend to be designed to higher standards, it is the already existing assets that will be most affected.
- It is worth noting as a final point that improved modelling of extreme climate events has been recognised as a priority by the international scientific community.

Policy-makers

- It is recommended that resources be invested in 'trusted' platforms for informing different stakeholders how to effectively access climate data, and then how to interpret it for their adaptation needs (including guidance for dealing with uncertainty). With the necessary resources, this is either an extended role that CSIRO could valuably perform or else it could be tasked to a 'boundary' organisation responsible for tailoring climate information and guidance as required by end users.
- Efforts towards greater standardisation of climate data between organisations and jurisdictions (timelines, use of different scenarios etc.) would help to establish a more consistent framework for risk assessment and informed adaptation planning across the country. CAWCR (a joint CSIRO / BoM initiative) is arguably well placed to champion greater consistency.
- Policy-makers will need to engage fully with the forthcoming set of IPCC scenarios and ensure that access and interpretation of this new resource by end-users is supported.
- Requiring major infrastructure owners and operators to conduct climate risk assessments, as is now the case in the UK, is a policy option that should be actively considered.

10.3 Undertaking an integrated assessment of risks

- Effective engagement with a range of different actors (scientific experts from multiple disciplinary backgrounds, information providers, seaports, practitioners, and policymakers) was a critical element affecting the success of the program of research.
- The importance of 'co-generating' knowledge cannot be underestimated and is highly recommended for the process of assessing climate risks.
- Climate risks are only one set of drivers facing future port operations, and it is therefore valuable to contextualise climate risks within a broader set of drivers. Ports will normally do this as part of their own in-house planning – their primary interest in this particular project was much more focused on gaining information about the climate science. For this project important non-climate drivers (demography, economy, technology, institutions, and supply chains) were addressed.

- Integrating climate and non-climate scenarios can be difficult mainly as a result of their respective time horizons; however any compromise in temporal scale needs to be attentive to the planning timeframes of port authorities.

Science / research

- The research project was underpinned by an integrated assessment methodology – this proved extremely useful for framing the key issues and ‘making sense’ of the complex mix of quantitative and qualitative information that needed to be considered when conducting a system-wide analysis of ports.
- As noted by the literature review, detailed studies of climate impacts on different infrastructure systems are limited (or not publicly accessible). Research continues to be needed on the climate risks, and adaptation options, relevant to Australia’s settlements and infrastructure.

Policy-makers

- It is important that initiatives that promote co-generation of knowledge continue to be supported.
- Studies looking at future risks to infrastructure would benefit from authoritative national level guidance on non-climate scenarios (e.g. potentially developed as part of the new National Freight Strategy) to provide a ‘common’ framework that underpins different assessments.
- Looking to international examples of how to apply an integrated assessment framework may also be useful (UK, the Netherlands etc.).

10.4 Adaptation opportunities

- Measures identified include ‘soft’ interventions such as the training of staff, ‘mainstreaming’ climate change considerations into existing risk management and other port policies, greater collaboration with other stakeholders to consider future risks, and identification of adaptation options. Knowledge exchange between ports is a key component of enhancing resilience and having a web-based resource which showcases best practice for the sector is likely to be extremely beneficial.
- Hard options include: changes to design standards and maintenance regimes, consideration of more innovative (flexible) engineering options (an adaptive management approach), ensuring that climate change is explicitly addressed as part and parcel of normal port planning cycles (though it is important to recognise that smaller ports may have less capacity to respond) etc.
- New policy developments, such as the introduction of national port and freight strategies, offer up a great opportunity for mainstreaming climate change considerations.

This multi-disciplinary, multi-institutional, project was a substantial undertaking. Each of the individual work package technical reports provides detail of the research carried out into understanding future risks and assessing the implications for different elements in the seaport environs: infrastructural assets, functional assets and operations, and the workforce. An additional report on adaptation guidelines and climate information packs for each of the case study ports are also available as outputs from the research project.

REFERENCES

- Australian Green Infrastructure Council (AGIC) (2010). AGIC Guidelines for Climate Change Adaptation. Available Online:
http://www.agic.net.au/agic_climate_change_adaptation_guideline_for_infrastructure.pdf
- Becker, A., Inoue, S., Fischer, M. and Schwegler, B. (2011). Climate Change Impacts on International Seaports: Knowledge, Perceptions, and Planning Efforts among Port Administrators, Ad Hoc Expert Meeting on Climate Change Impacts and Adaptation: A Challenge for Global Ports, 29-30th September 2011. Available Online:
http://archive.unctad.org/sections/wcmu/docs/AHM2011_2_18_Becker_en.pdf
- Clarke, J.M., Whetton, P.H. and Hennessy K.J. (2011). Providing application-specific climate projections datasets: CSIRO's Climate Futures Framework, 19th International Congress on Modelling and Simulation, Perth, Australia, 12–16 December 2011. Available Online:
<http://www.mssanz.org.au/modsim2011/F5/clarke.pdf>
- Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BoM) (2007). Climate Change in Australia: Technical Report 2007. CSIRO Publishing, Canberra. Available Online:
http://www.climatechangeinaustralia.gov.au/technical_report.php
- Cox R, McEvoy, D., Allen, G., Bones, A. and McKellar, R. (2012). National Climate Change Adaptation Research Plan: Settlements and Infrastructure – Update Report. National Climate Change Adaptation Research Facility, Gold Coast. Available Online:
http://www.nccarf.edu.au/sites/default/files/attached_files_publications/SI%20NARP%20Update%20Report%20FINAL.pdf
- Dovers, S. (2009). Normalizing Adaptation, *Global Environmental Change*, 19(1): 4-6.
- Engineers Australia (2010). Infrastructure Report Card 2010: Australia. Engineers Australia, Barton. Available Online:
<http://www.engineersaustralia.org.au/sites/default/files/shado/Infrastructure%20Report%20Cards/Australian/2010%20Australian%20IRC%20Report.pdf>
- Fünfgeld, H. and McEvoy, D. (2011). Framing Climate Change Adaptation in Policy and Practice. Melbourne: VCCCAR. Available Online:
http://www.vcccar.org.au/files/vcccar/Framing_project_workingpaper1_240611_0.pdf
- Hallegatte S., Patmore, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., Muir Wood, R. (2008). Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen, OECD Environment Working Papers No.3.
- Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Mortlot, J., Herweijer, C. and Chateau, J. (2011). A global ranking of port cities with high exposure to climate extremes, *Climatic Change* (104): 89-111.
- Hennessy K., J. Clarke, P. Whetton and D. Kent (2012). An introduction to internally consistent climate projections CSIRO, Aspendale.
- HM Government (2010). Climate Change: Taking Action. Delivering the Low Carbon Transition Plan and preparing for a changing climate. Crown Copyright, United Kingdom.

Hunter, J. (2010). Estimating sea-level extremes under conditions of uncertain sea-level rise, *Climatic Change*, 99:331-350.

Infrastructure Australia (2011). National Ports Strategy: Infrastructure for an economically, socially, and environmentally sustainable future, Infrastructure Australia and the National Transport Commission, Commonwealth Government, Canberra. Available Online: http://www.infrastructureaustralia.gov.au/gateways/files/National_Ports_Strategy_DEC2010_v2.pdf

Infrastructure Australia (2012). Australian infrastructure: progress and action. A report to the Council of Australian Governments, Infrastructure Australia. Available Online: http://www.infrastructureaustralia.gov.au/2012_coag/files/P195_IACOAG%202012_FullReport_WS.pdf

Institution of Engineers, Australia (2000). Research Priorities for Coastal and Ocean Engineering. Available online:

http://www.engineersaustralia.org.au/sites/default/files/shado/Learned%20Groups/National%20Committees%20and%20Panels/Coastal%20and%20Ocean%20Engineering/Research_Priorities_Coastal_Ocean_Eng_Aust.pdf

Intergovernmental Panel on Climate Change (IPCC) (2007). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC) (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

International Association of Ports and Harbors (IAPH) (2011). Seaports and Climate Change – An Analysis of Adaptation Measures, Port Planning and Development Committee, International Association of Ports and Harbours, Hamburg, Germany.

Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Chateau, J. and Muir Wood, R (2008). Ranking port cities with high exposure and vulnerability to climate extremes: exposure estimates, Environment Working Papers no.1, OECD.

Nicholls, R.J., Brown, S., Hanson, S. and Hinkel, J. (2010). Economics of Coastal Zone Adaptation to Climate Change. Discussion Paper No. 10. World Bank, Washington DC. Available Online:http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2010/10/27/000333038_20101027000904/Rendered/PDF/574750Revised01stal0Zone0Adaptation.pdf

Peel Ports Group (2011). Mersey Docks and Harbour Company Ltd. Climate Change Adaptation Report, Report to DEFRA under the Adaptation Reporting Powers, Peel Ports Group. Available Online: <http://archive.defra.gov.uk/environment/climate/documents/adapt-reports/07ports/mersey-docks-harbour.pdf>

Permanent International Association of Navigation Congresses (PIANC) (2008). Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation. EnviCom – Task Group 3 Climate Change and Navigation, PIANC, Brussels. Available Online: <http://www.pianc.org/downloads/envicom/envicom-free-tg3.pdf>

Ports Australia (n.d.). Map of the Ports of Australia. Available Online:
<http://www.portsaustralia.com.au/misc/Ports%20Australia%20map.pdf>

Stenek, V., Amado, J-C., Connell, R., Palin, O., Wright, S., Pope, B., Hunter, J., McGregor, J., Morgan, W., Stanley, B., Washington, R., Liverman, D., Sherwin, H., Kapelus, P., Andrade C. and Pabon, J.D. (2011). Climate Risks and Business Ports: Terminal Martimo Muelle et Bosque Cartagena, Colombia, World Bank.

United Kingdom Climate Impacts Program (UKCIP) (2007). Identifying Adaptation Options, Available Online: http://www.ukcip.org.uk/wordpress/wp-content/PDFs/ID_Adapt_options.pdf

United Kingdom Climate Impacts Program (UKCIP) (2011) AdOpt: Guiding Principles, Available Online: <http://www.ukcip.org.uk/adopt/guiding-principles/>

APPENDIX 1: LIST OF PROJECT STAKEHOLDERS

Jeroen Aerts	International 'Port Cities' network	Vrije Universiteit, The Netherlands
David Anderson	CEO	Ports Australia
Owen Barton	Port Infrastructure Asset Manager	Gladstone Ports Corporation
Alan Betts	Chairman	Engineers Australia NSW Maritime Panel
Mario Blasi	Port Operations Manager (PK)	BlueScope Steel
Trevor Brown	Environmental Sustainability Officer	Port Kembla Port Corporation
Jerome Carslake	Manager, Strategic Research & Planning	National Transport Commission
Gary Carter	Acting Port Planning and Development Manager	Gladstone Ports Corporation
Robert Cechet	Sen. Res. Scientist RISK Research Group, Geospatial & Earth Monitoring Div.	Geoscience Australia
Alex Chalk	Risk Manager	Port Kembla Coal Terminal
John Clarke	Project Manager – Climate Projections Liaison	CSIRO – Marine & Atmospheric Research
Doyle Cook	General Manager	Port Kembla Gateway Pty Ltd
Ron Cox	Convenor	Settlements & Infrastructure Network, NCCARF
Lori Dalton (and Mark Dossetor)	Freight, Logistics and Marine Division	Victorian Department of Transport
Hans de Moel	International 'Port Cities' network	Vrije Universiteit, The Netherlands
Andrew Dunne	General Manager, Engineering & Environment	Port Kembla Port Corporation
Dom Figliomeni	Chief Executive Officer	Port Kembla Port Corporation
Susan Fryda-Blackwell	EO	Ports Australia
Glenda Graham	Executive Director, Victoria Division	Engineers Australia

Lana Howell	Port Kembla Terminal Manager	AAT
Jason Humphreys	Director Rail & Ports Policy and GOC Governance	Rail, Ports and Freight Division, Qld govt.
Greg Hunt	Executive Officer	South East Councils Climate Change Alliance
Agata Imielska	Climatologist, Climate Monitoring	Bureau of Meteorology
Mark Ireland	Sustainability Manager	Sydney Ports Corporation
Belinda Irwin	Senior Policy Analyst	National Transport Commission
Mark Jelbart	Manager – Port Kembla Terminal	Graincorp Operations Limited
Rachel Johnson	Deputy Director General Freight and Regional Development	Transport NSW
Sandra Johnson	Project Officer	Port of Hastings Development Authority
Alison Karwaj	Environmental Coordinator	Sydney Ports Corporation
Rodney Keenan	Director	VCCCAR
Christopher Lee	Manager, Impacts & Adaptation	Office of Environment & Heritage, NSW Govt
Shoni Maguire	CAWR Support Manager	Bureau of Meteorology
Kathy McInnes	Research Scientist, sea level rise and coasts team	CSIRO – Marine & Atmospheric Research
Raphael Miller	Senior Commercial Analysis	Sydney Ports Corporation
Rod Pickette	National Policy Executive Officer	Maritime Union of Australia
Phill Piper	Director, Land Development and Infrastructure, Strategic Lands Planning	Dept. of Lands and Planning, NT
David Robinson	Snr Director	Queensland Climate Change Centre of Excellence
Llew Russell	CEO	Shipping Australia Ltd
John Sherriff	Environmental Manager	Gladstone Ports Corporation
Fotios Spiridonos	Director – Transport Modelling & Mapping	Department of Transport, Vic govt.

Anthony Sprigg	CEO	Australian Green Infrastructure Council
Amanda Thomas	Director, Research and Policy	Transport and Logistics Industry Skills Council
Bill Vrontas	Maintenance Engineer	Sydney Ports Corporation
David Walland	Manager Climate Services, Climate & Water Division	Bureau of Meteorology
Rick Walters	Technical Director	Australian Green Infrastructure Council
Xiaoming Wang	Principal Research Scientist, Ecosystem Sciences	CSIRO
Chris White	Principal Scientist, Climate Systems Research	Queensland Climate Change Centre of Excellence (QCCCE)
Robert Wilby	Professor of Hydroclimatic Modelling	Loughborough University, UK

APPENDIX 2: CLIMATE INFORMATION PACKS FOR THE CASE STUDY PORTS

Climate Risk Information

Climate Change Scenarios and Implications for Port Botany, Sydney

Climate Change Adaptation Program, RMIT University



Climate Risk Information

Climate Change Scenarios and Implications for Port Botany, Sydney

September 2012

Lead authors

Sophie Millin, Climate Change Adaptation Program, RMIT University

Jane Mullett, Climate Change Adaptation Program, RMIT University

Acknowledgements

The content covered in this guide draws not only on direct contributions from the collaborators mentioned above but also from a range of individuals within BOM and CSIRO. The project team would like to thank the following people in the development of this guide: Leanne Webb and Penny Whetton from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Shoni Maguire from the Bureau of Meteorology (BOM). We also acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Disclaimer

The forward climate projections in this document were created with the support of the CSIRO. The Data describes possible futures. They are not predictions. Please note that any use of the Data is solely at the Recipient's own risk.

Cover photo

Aerial photograph of Port Botany (Image: www.metrostrategy.nsw.gov.au)

TABLE OF CONTENTS

1	INTRODUCTION	1
1.1	Purpose of this report.....	1
1.2	Port Botany and the Sydney/Central coast region	1
2	OBSERVED CLIMATE IN NEW SOUTH WALES	2
2.1	Temperature.....	2
2.2	Precipitation	4
2.3	Sea level rise	5
2.4	Extreme Weather Events.....	6
3	FUTURE CLIMATE PROJECTIONS	8
3.1	Global Climate Models, emissions scenarios and time periods	8
3.2	Atmospheric Projections	9
3.3	Ocean Projections.....	11
3.4	Extreme Weather Events.....	15
4	FURTHER READING	17

List of Figures

Figure 1	The Sydney/Central coast region within New South Wales.
Figure 2	NSW annual mean surface temperature anomaly, 1910–2011
Figure 3	Average annual rainfall in NSW, 1900-2011
Figure 4	Trend in annual total rainfall (mm/10 years) for the 1970-2010 period.
Figure 5	Rate of sea level rise around Australia from January 1993 to December 2011.
Figure 6	The number of very hot days (days over 40°C) across Australia.
Figure 7	Port Botany pilot boat struggling through severe swell, June 2012
Figure 8	Annual carbon emissions in billion tonnes for 1990-2010
Figure 9	The spatial pattern of thermal expansion around east coast Australia
Figure 10	Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m.

List of Tables

Table 1	20 Warmest years in NSW (relative to 1961–1990) since 1910
Table 2	Baseline climate and projected annual surface temperature change
Table 3	Baseline climate and projected annual precipitation change
Table 4	Baseline climate and projected annual relative humidity change
Table 5	Sea level change (m) over the 21 st century with respect to 1990.
Table 6	Components of sea level rise
Table 7	Baseline climate and projected annual sea surface temperature
Table 8	Baseline climate and projected annual sea surface salinity
Table 9	Baseline climate and projected days per annum over 35 degrees Celsius
Table 10	Baseline climate and projected days per annum over 40 degrees Celsius
Table 11	Baseline climate and projected summer days over 35 degrees Celsius
Table 12	Baseline climate and projected summer days over 40 degrees Celsius
Table 13	Baseline climate and projected annual extreme precipitation change
Table 14	Baseline climate and projected summer extreme precipitation change
Table 15	Baseline climate and projected annual extreme wind speed change

1 INTRODUCTION

This report provides information on observed climate change within New South Wales and future climate projections for the Sydney/Central Coast region, and Port Botany specifically within New South Wales.

1.1 Purpose of this report

This report has been produced to provide accessible and relevant climate information for Port Botany and Sydney Ports Corporation, in New South Wales. Both past climate observations and future climate projections are described.

The report focuses on the state of New South Wales for the observed climate and the local government region of Sydney/Central Coast for the future climate projections. Information has been taken from the following publicly available sources:

- Bureau of Meteorology's website on *Australian Climate Extremes*
- NSW Government reports on *Observed Changes in New South Wales climate 2010* and *New South Wales Climate Impacts Profile*
- CSIRO and Bureau of Meteorology *Climate Change in Australia*
- CSIRO's Marine and Atmospheric Research website on *Sea Level Rise*

In producing the report the authors note that the NSW Government reports only project as far forward as 2050. This report draws on these reports and also aims to provide a longer term view by looking to 2070 and 2100. In doing so, the authors hope that the port authorities have the resources to make

more informed decisions for adapting to long-term climate change. The following areas have been looked at with respect to their potential to impact the function of the harbour authority:

- Temperature and precipitation
- Relative humidity
- Sea level rise
- Sea surface temperature and salinity
- Extreme weather events

1.2 Port Botany and the Sydney/Central Coast region

Port Botany sits within the Sydney/Central coast region of NSW, between the Hunter region to the north and the Illawarra region to the south (Figure 1). The region's 120 km coastline extends from the Royal National Park to the southern shores of Lake Macquarie, and its numerous estuaries include drowned rivers such as Broken Bay, Sydney Harbour, Botany Bay and Port Hacking. Most of the region has a warm temperate climate. Average annual rainfall in greater Sydney ranges from more than 1200 mm near the coast to slightly less than 800 mm in the west. Rainfall throughout the region is greatest in summer and autumn, with a slightly higher proportion of winter rainfall on the coast than inland.

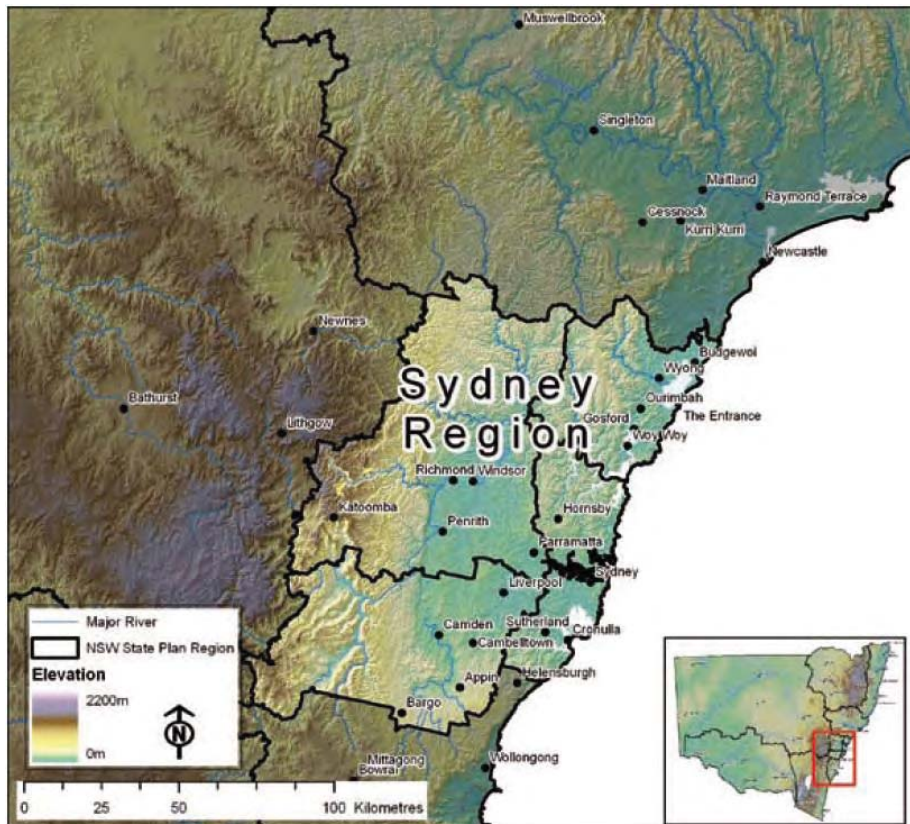


Figure 1. The Sydney/Central Coast region within New South Wales. Source: www.environment.nsw.gov.au © State of NSW and Department of Environment, Climate Change and Water NSW.

2 OBSERVED CLIMATE IN NEW SOUTH WALES

This section presents observed climate information for temperature, precipitation, sea level rise and extreme weather events in New South Wales.

2.1 Temperature

New South Wales (NSW) is described as having a temperate climate with warm summers and cool winters, although the climate undergoes large variations depending on the proximity to the coast and mountains (Office of Environment and Heritage 2011).

Records show an annual average air temperature of 17.3°C from 1961 to 1990. This average has been increasing at an accelerating rate since the mid-1990s, based on current climate trends (Figure 2).

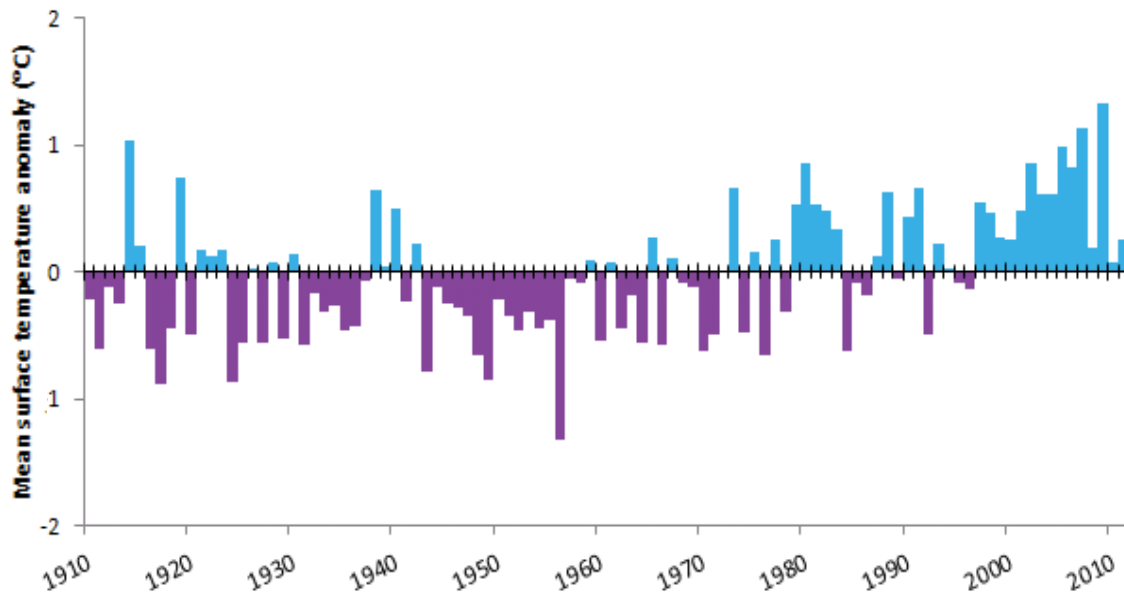


Figure 2: NSW annual mean surface temperature anomaly, 1910–2011 Source: Bureau of Meteorology.

Ranking	Year	Temperature difference
1	2009	+1.33
2	2007	+1.13
3	1914	+1.04
4	2005	+0.99
5	1980	+0.86
6	2002	+0.85
7	2006	+0.83
8	1919	+0.75
9	1991	+0.67
10	1973	+0.66

Ranking	Year	Temperature difference
11	1938	+0.65
12	1988	+0.63
13	2003	+0.61
14	2004	+0.61
15	1997	+0.55
16	1979	+0.54
17	1981	+0.54
18	1940	+0.5
19	1982	+0.49
20	2001	+0.49

Table 1: 20 Warmest years in NSW (relative to 1961–1990) since 1910. Source: Bureau of Meteorology.

2.2 Precipitation

Annual rainfall in NSW has been highly variable. There have been very dry years (such as 1940 and 2002) and very wet years (such as 1950, 1974 and recently in 2010) and generally these correlate with the dry El Nino years and wet La Nina years. With respect to the average rainfall for NSW, the

past 50 years has seen a slight decline compared with the very wet years of the 1950s (Figure 3). However, since the beginning of the 20th century, NSW as a whole has not seen an overall downward trend in rainfall. Figure 4 shows how the NSW coast has experienced a drying trend over the past 40 years.

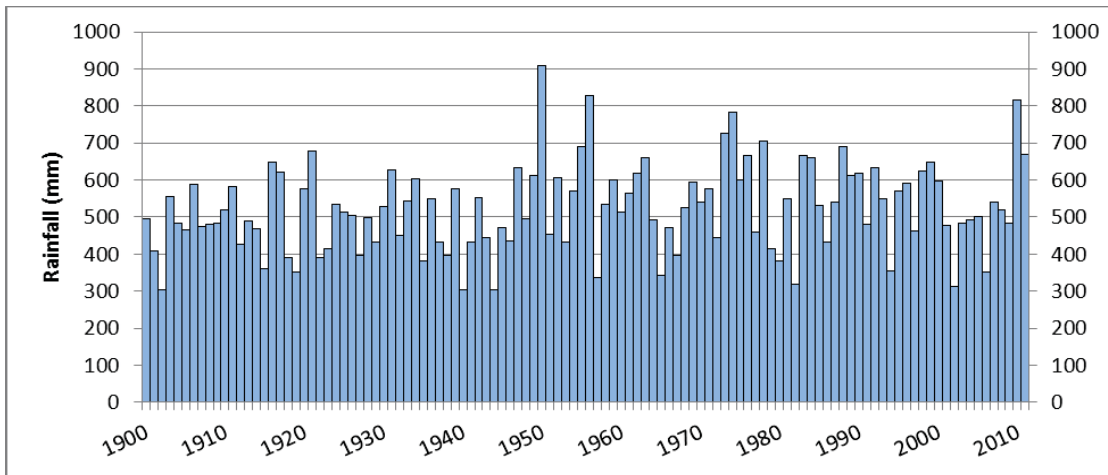
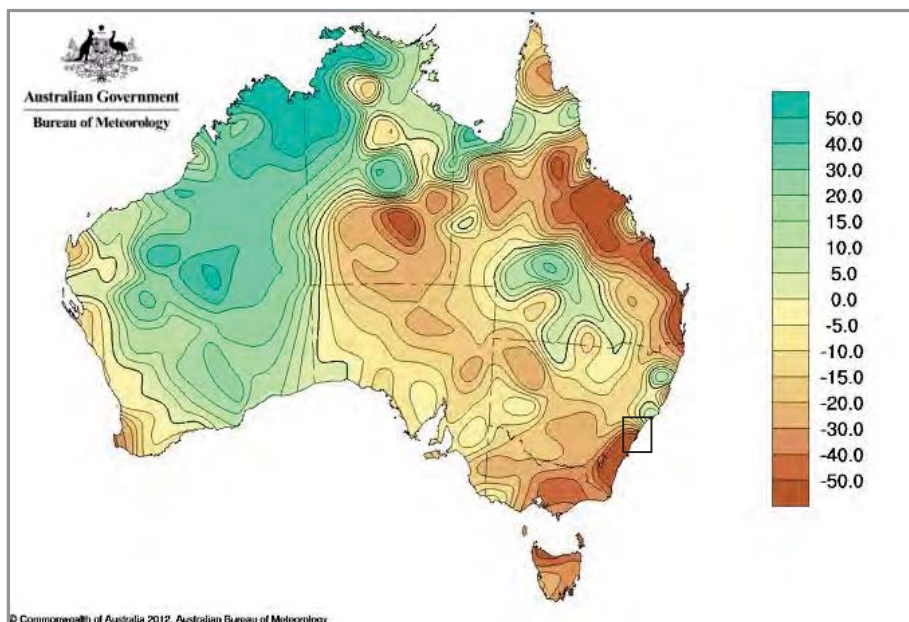


Figure 3: (Above) Average annual rainfall in NSW, 1900-2011 Source: Bureau of Meteorology.

Figure 4. (Below) Trend in annual total rainfall (mm/10 years) for the 1970-2010 period. The Sydney region is shown by the box. Source: Bureau of Meteorology.



2.3 Sea level rise

Globally, sea levels have risen by about 20cm since 1870. Tide gauge measurements available since the late 19th century indicate that sea levels have risen by 1.7 ± 0.3 mm/year since 1950. This figure increases from 1993 to 2011 to 3.1 ± 0.4 mm/year suggesting that sea level rise is accelerating.

Across Australia, sea levels have risen 7 to 11 mm per year in the north and northwest, two to three times the global average, whereas rates of sea-level rise on the central east and southern coasts of the continent are mostly similar to the global average (Figure 5). These regional variations are largely due to differences in the warming of the ocean waters around the coastline.

The rate of sea level rise has not been even around the world, but the average rise in eastern Australia has been between 24 and 48 millimetres since 1994, which is a rate of 1.4-2.8mm a year. Sea level at Port Kembla, just south of Sydney, has risen about 60 millimetres since 1991 which is a slightly higher rate of 3mm a year.

Rising sea levels have significant repercussions for much of NSW, where 85% of the population live within 50km of the coastline (Australian Bureau of Statistics 2001). High tide events give some indication of what the impacts of sea level rise could mean. A high tide in Sydney, in 2009, resulted in sea water encroaching onto roads and approaching houses. Flooding in estuaries and some coastal lakes will be exacerbated by higher sea levels.

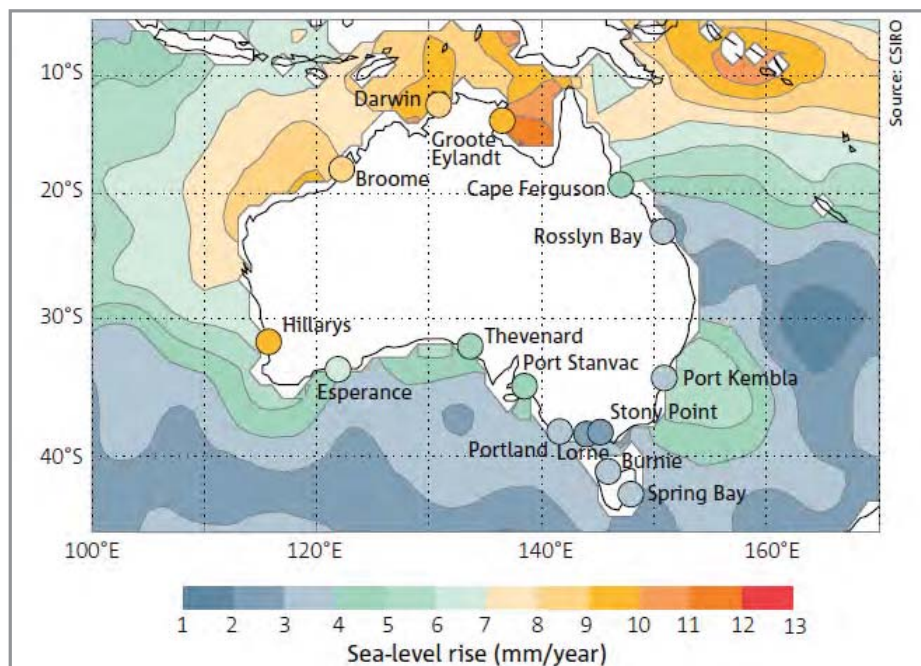


Figure 5. Rate of sea level rise around Australia as measured by coastal tide gauges (circles) and satellite observations (contours) from Jan 1993 to Dec 2011.

Source: (CSIRO & Bureau of Meteorology 2012)

2.4 Extreme weather events

The meteorological or statistical definition of extreme weather events are events at the extremes (or edges) of the complete range of weather experienced in the past. Defined in this way, extreme weather events include, but are not limited to, events like heat waves or intense rainfall.

The climate variables explained here include temperature, precipitation and sea level rise. Each of these operates at a variety of timescales. When experienced in limited duration, they are referred to as an extreme event. A heat wave is an example of a temperature-related extreme event. For precipitation, the extreme event timescales are asymmetric; heavy precipitation events generally range from less than one hour to a few days, whereas droughts can range from months to years. And while sea level rise is a gradual process, storm surges represent short-term high-water levels superimposed onto mean sea level. These are generally as a

result of strong onshore winds and/or reduced atmospheric pressure.

2.4.1 Heat waves

Although there is no universal definition of a heat wave, it can be defined as a prolonged period of excessive heat. When using data to examine heat waves, two parameters can be used: hot days and very hot days; days that maximum temperatures exceed 35°C and 40°C, and heat waves; three consecutive days of 35°C and above.

Between 1970 and 2011, the number of hot days (days over 35°C) in NSW increased, in some areas by up to 7.5 days per decade. The number of heat waves in a given year is highly variable. For example, in 2009, NSW experienced three heat waves in January, August and November with temperatures exceeding 37 degrees. However in 2010, maximum temperatures were the coolest since 1992 at 0.47 °C below the 1961-1990 average.

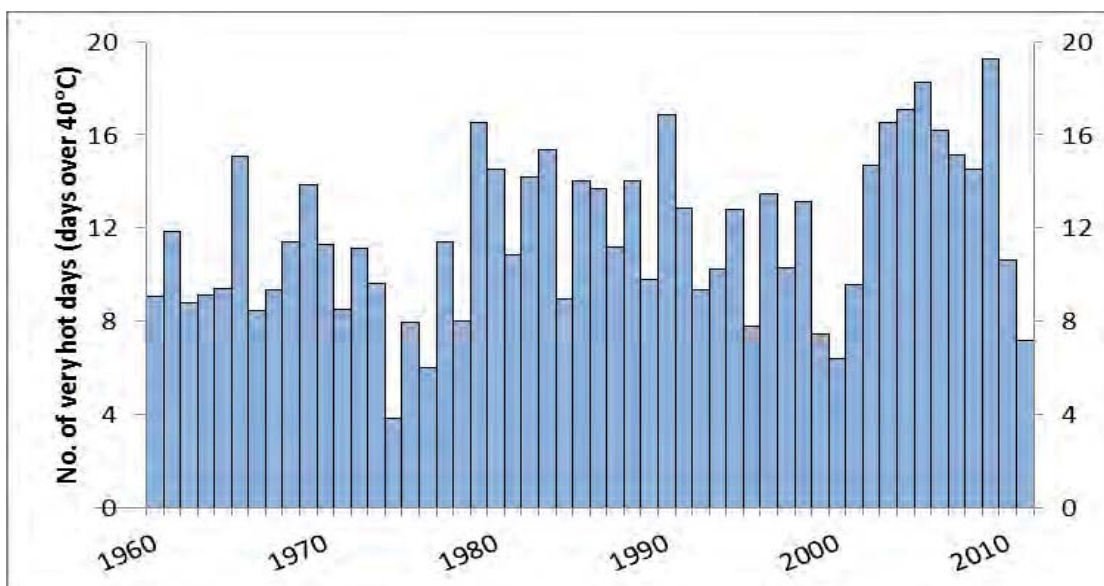


Figure 6. The number of very hot days (days over 40°C) across Australia.

Source: Bureau of Meteorology.

2.4.2 Extreme precipitation

From 1950 to 2005, extreme daily rainfall intensity and frequency increased in north-western and central Australia and over the western tablelands of New South Wales, but decreased in the south, south-east, south-west and along the central east coast (IPCC 2007a).

Most recently, New South Wales experienced widespread and persistent heavy rainfall in both February 2011 and March 2012. Both of these events were associated with strong La Niña conditions which generally result in above average rainfall across eastern and northern Australia. The total rainfall recorded for March 2012 was 119.59mm, more than half the average for NSW, making 2012 the second wettest March since 1956.

In the Sydney region, two of the most significant rainfall events were caused by pressure systems known as east coast lows (see below). These weather events both occurred in June, one in 2007 and one in 2012. In 2007, five lows each brought varying amount of rainfall but the first, on the June 8-9 was the most serious causing major flooding, beach erosions and huge swells. On the 9th June, the maximum daily rainfall was recorded at Mangrove Mountain. 293.6 mm in just 24 hours.

2.4.3 East Coast Lows

East Coast Lows (ECL) are intense low-pressure systems which occur on average ten times a year off the eastern coast of Australia. Although they can occur at any

time of the year, they are more common during Autumn and Winter with a maximum frequency in June. East Coast Lows will often intensify rapidly overnight making them one of the more dangerous weather systems to affect the NSW coast.

The most recent East Coast Lows to affect NSW were in June 2012. One caused heavy rain up the coast which was coupled with very strong wind gusts, reaching 117 km/hr at Port Botany. Large waves and coastal erosion were also reported, with maximum wave heights reaching 13.8m at Sydney. The second East Coast Low developed off the north coast on the 10th, with widespread rain between Tweed Heads and Wollongong on the 11th and 12th, heaviest in the Yamba and Sydney regions. This had weaker wind impacts, with a maximum gust of 91 km/hr at Byron Bay on the 12th, and maximum wave heights of 11.3 m at Byron Bay.



Figure 7. Storm Sky © Ian Sanderson, Flickr

3 FUTURE CLIMATE PROJECTIONS

This section provides information on Global Climate Models, emissions scenarios and time periods. It also details future projections for atmospheric and ocean variables as well as a final section on extreme weather events.

3.1 Global Climate Models, emissions scenarios and time periods

Global climate models (GCMs) are mathematical representations of the behaviour of the planet's climate system through time. Each mathematical equation is the basis for complex computer programs used for simulating the atmosphere or oceans of the Earth. In this study, four models were selected by considering the alignment of model results over the regions of Sydney/Port Kembla and also Gladstone, as defined by the CSIRO's Climate Futures software (Whetton et al. 2012). 18 climate models were sub-divided into pre-defined categories such as "Hotter, Drier" and then assigned a relative likelihood based on the number of climate models that fell within that category. For example, if 9 of 18 models fell into the "Warmer – Drier" category, it was given a relative likelihood of 50% (Clarke et al. 2011). The models selected for Port Botany were:

- i. **MRI-CGCM2.3.2** - A 'most likely'* future: hotter and little change in rainfall.
- ii. **CSIRO MK3.5** - A 'hot/dry' future: much hotter and much drier.
- iii. **MIROC3.2-Medres** - A 'wetter' future: cooler and wetter.
- iv. **MIROC3.2-Hires** – A 'wetter' future: slightly warmer and wetter.

*Category represented by the greatest number of models.

Modelling future climate change requires an estimation of the concentrations of greenhouse gases and other substances in the atmosphere, in the years to come. **Emissions scenarios** describe these future releases and are the product of complex dynamic systems, determined by factors such as population change, socio-economic development, and technological advances. The two emissions scenarios that were available and selected by the research team were from the 'A1 storyline' and were developed by the IPCC Special Report on Emissions Scenarios (SRES). These scenarios are labelled based on their relative greenhouse gas emissions levels, High (SRES A1FI) and Medium (SRES A1B). The team chose not to represent a Low emissions scenario (SRES B1) as much of the literature suggests this scenario may underestimate future emission scenarios (Raupach et al. 2007; Friedlingstein et al. 2010) see Figure 8.

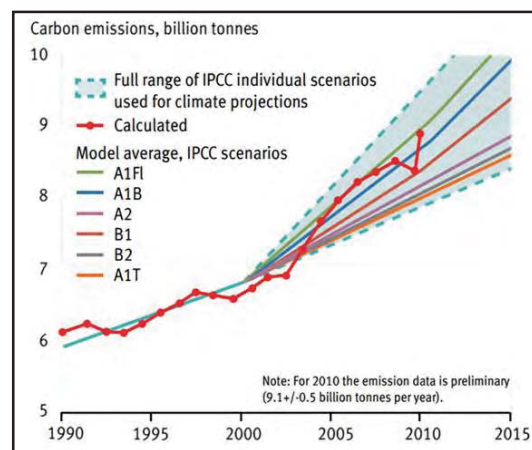


Figure 8. Annual carbon emissions in billion tonnes for 1990-2010. Source: (UNEP 2012)

GCMs project the likely range of changes over decadal to multi-decadal time periods. These **time periods** are expressed relative to the given baseline period and are centred on a given decade. So, the 2050s time period refers to the period 2040-2069. Thirty year time periods provide an average over this range, cancelling out much of the random year-to-year variability. This study focuses on three time periods; the 2030s, 2050s and 2070s.

3.2 Atmospheric projections

The results presented in this section (Tables 2, 3 and 4) show the projected change from the 1975-2004 baseline climate. Data is provided for three time periods and for three models. The 'wetter' model in these projections is based on the MIROC3.2-Medres model. The range shown is from the medium (A1B) to the high (A1FI) emissions scenario.

3.2.1 Temperature

Annual mean temperature projections for Port Botany (Table 2) show that there is likely to be a slight increase by the 2030s, with a projected increase of 0.7 to 1.2 degrees Celsius (°C) above 1975-2004 values, across the three models. By the 2050s this increases to 1.4 to 2.9°C. Much larger ranges are projected for the 2070s, with increases from 1.7 to 4.0°C above the baseline climate. For Port Botany, annual mean temperatures may increase from 16.4°C to between 17.8 and 19.3°C in 2050, and to between 18.1 and 20.4°C by 2070. Temperatures of 20°C are equivalent to annual mean temperatures in Brisbane. Despite temperature increases for the 2030s being relatively modest, a small increase in mean temperature can lead to a large increase in the frequency and severity of

extreme heat events. There is also not a large distinction between the emissions scenarios until after the 2030s as temperature patterns do not distinguish from each other until after this period. This is due to the time it takes for each emissions scenario to produce large differences in greenhouse gas concentrations.

3.2.2 Precipitation

Rainfall in coastal regions is difficult to simulate due to changes in weather patterns that cannot be resolved by climate models. This creates a large range of uncertainty for precipitation projections (Table 3). For the 2070s, the 'hotter and drier' model shows decreases of between -10.4 to -14.1%. However, the 'wetter' model projects increases in precipitation of 8.5 to 11.5%. The *NSW Climate Impact Profile* examines seasonal projections and suggests that for the 2050s, the Sydney/Central Coast region is likely to experience a significant rainfall increase of between 20-50% in the summer, a 10-20% increase in spring, no significant change in autumn and a 10-20% decrease in winter.

3.2.3 Relative humidity

Relative humidity projections show decreases for all time periods for the 'most likely' and 'hotter and drier' models (Table 4) which reflect the average projections across Australia. For the 2030s, the 'most likely' model ranges from -0.8 to -0.7% change. By the 2050s, this range increases to -1.4 to -1.8% and by 2070 the reductions are between -1.8 and -2.5% change. The 'hotter and drier' model shows larger reductions for all three time periods, from -2.7 to -2.6% for 2030, -5.0 to -6.3% for 2050 and -6.4 to -8.7% for 2070.

Temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	17.3	0.7	0.7	1.4	1.7	1.7	2.3
'Hotter and drier'	17.3	1.2	1.2	2.3	2.9	2.9	4.0
'Wetter'	17.3	0.7	0.7	1.4	1.7	1.7	2.3

Table 2. Baseline climate and projected annual surface temperature change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Precipitation (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	1030	-0.4	-0.4	-0.7	-0.9	-0.9	-1.3
'Hotter and drier'	1030	-4.4	-4.2	-8.2	-10.2	-10.4	-14.1
'Wetter'	1030	3.6	3.4	6.7	8.3	8.5	11.5

Table 3. Baseline climate and projected annual precipitation change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Relative Humidity (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	74.5	-0.8	-0.7	-1.4	-1.8	-1.8	-2.5
'Hotter and drier'	74.5	-2.7	-2.6	-5.0	-6.3	-6.4	-8.7
'Wetter'	74.5	0.8	0.8	1.5	1.8	1.9	2.5

Table 4. Baseline climate and projected annual relative humidity change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

3.3 Ocean projections

3.3.1 Sea-level rise

Mean sea level rise occurs due to two main processes; the melting of land based ice, which increases the mass of the ocean, and decreases in ocean density, which increases the volume of the ocean. The latter mainly occurs due to increases in the heat content of the oceans which is referred to as thermal expansion.

The IPCCs Fourth Assessment Report (IPCC 2007) projects global mean sea level rise at between 0.21 and 0.59m for the medium and high emissions scenario. Concerns that these projections may have been underestimated (Rahmstorf et al. 2007) have led CSIRO's Centre for Marine and Atmospheric Research (CMAR) to produce updated figures. These projections are based on outputs from the

climate models and include changes in ocean temperature used to estimate changes in sea level due to thermal expansion and estimated flow rates from Greenland and Antarctica (Table 5). The figures show a projected global sea level rise of between 0.22 and 0.81m for the medium and high emission scenario.

As sea levels do not rise uniformly around the globe, regional variations need to be taken into account. Figure 9 shows projections around the Australian coastline. The top panel shows the difference between projected sea level and the global average with the average of all the models shown with the heavy blue line. The bottom panel allows for the identification of regional sea level rise projections at specific locations around the coastline. Each number corresponds with the top panel numbers.

	Medium			High		
	5th percentile	Central estimate	95th percentile	5th percentile	Central estimate	95th percentile
1990	0	0	0	0	0	0
2000	0.01	0.02	0.03	0.01	0.02	0.03
2010	0.02	0.04	0.06	0.02	0.04	0.06
2020	0.04	0.07	0.09	0.04	0.07	0.1
2030	0.06	0.1	0.14	0.06	0.1	0.14
2040	0.08	0.14	0.19	0.08	0.14	0.20
2050	0.1	0.18	0.25	0.1	0.18	0.27
2060	0.12	0.22	0.32	0.13	0.24	0.35
2070	0.15	0.27	0.39	0.16	0.31	0.45
2080	0.17	0.32	0.47	0.19	0.38	0.56
2090	0.19	0.37	0.55	0.23	0.45	0.68
2100	0.22	0.43	0.64	0.27	0.54	0.81

Table 5: Global sea level change (m) over the 21st century, including rapid ice sheet melt, with respect to 1990. The figures shown are for the medium (A1B) and high (A1FI) emissions scenarios, with 5th to 95th percentile confidence intervals. Figures are based on methods outlined in the IPCC's Fourth Assessment Report (Meehl et al. 2007). Source: http://www.cmar.csiro.au/sealevel/sl_proj_21st.html

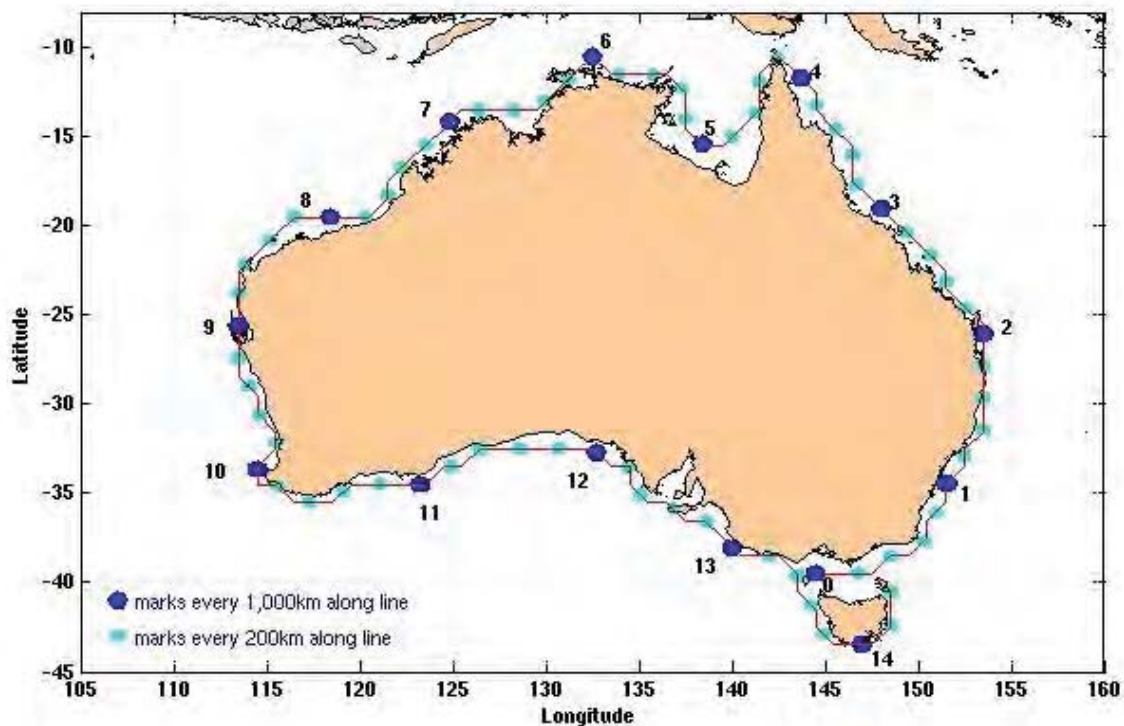
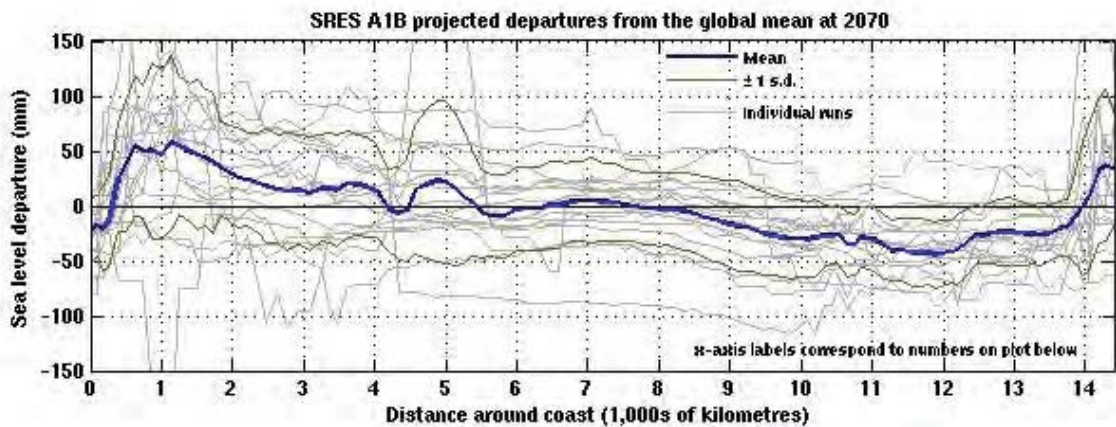


Figure 9: Regional sea level rise projections around the Australian coastline. Figures are derived from the 2070 globally-averaged mean projections for the A1B SRES scenario Source: http://www.cmar.csiro.au/sealevel/sl_proj_regional.html

Table 6 shows projections for global sea level rise together with regional projections taken from 1137km around the coast, or close to point 1 on the map of Figure 9. This point is the location closest to the latitude and longitude of Port Botany. The sea level rise

projections for Port Botany in 2030 and 2070 is 17.5 and 50.7cm. It should be noted that sea levels will continue to rise after 2070 and long-term planning should take into account projections after this date.

Component	2030	2070
Sea level rise (m) taken from high emission scenario (Table 5)	0.14m	0.39
Regional sea level rise variation	0.035m	0.057m
Total	0.175m (17.5cm)	0.447m (44.7cm)

Table 6: Components of sea level rise including CSIRO’s updated CMAR figures together with regional projections derived from the global average (see Figure 9).

Sea-level rise will create a significant risk to properties, infrastructure and beaches along the coastal areas of NSW (Steffen & Hughes 2012). The main threats from sea-level rise will be:

1. Storm-related flooding
2. Flooding from higher sea levels
3. Erosion of the land

1. Storm surge flooding

During severe storm events the impacts of sea-level rise are more apparent. When a storm event coincides with a storm surge and high tide, small rises in sea level can result in very large increases in the frequency of coastal flooding (ACE CRC 2008; J. Church et al. 2006). Around Sydney, flooding that is currently considered a 1-in-100 year event could occur every few months with a sea-level rise of 0.5m (Figure 10).

2. Flooding from higher sea levels

With a 1.1m rise in sea level in NSW:

- Parts of Sydney airport, the busiest in Australia, would be flooded with a storm surge, interrupting operations and damaging infrastructure
- Over 170km of railway would be at risk, with a replacement value of up to \$1.3

billion. Wollongong and Newcastle have the longest lengths of railway of NSW cities at risk from a 1.1m sea-level rise – 43–51 km and 49–56 km respectively (DCCEE 2011).

3. Erosion

Higher sea levels can cause erosion of beaches, and the retreat of soft coastlines further inland. Coastal erosion can undermine buildings, such as seaports and infrastructure, such as roads and railways. Approximately 3,600 residential buildings in NSW are located within 110 metres of soft shorelines (Steffen & Hughes 2012).

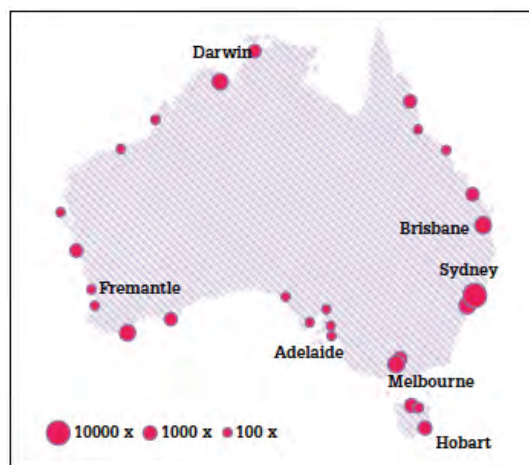


Figure 10. Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m. Source ACE CRC 2008.

3.3.2 Ocean temperature and salinity

This section considers the temperature of the sea surface (or sea-surface temperature - SST) and sea-surface salinity (SSS). As before, projections are derived for three 30-year time periods centred on 2030, 2050 and 2070, relative to the 1975 to 2004 baseline. The research team aimed to keep all of the variables consistent, however, the MIROC3.2 Medres model was not available for sea surface temperature and only 'wetter' models were available for salinity. The MIROC3.2-Hires model therefore replaces

the MIROC3.2 Medres model in the sea surface temperature results and is the only model used in the salinity results.

Sea-surface temperatures for the Port Botany region, are projected to increase by 0.6 to 1.0°C for the 2030s, 1.1 to 2.1°C for the 2050s and 1.5 to 3.4°C for the 2070s.

Sea-surface salinity (SSS) is the measure of the concentration of dissolved salt in the sea water, at, or very close to the ocean surface. Sea-surface salinity projections show no significant change with an increase in practical salinity units (psu) from 35.5 to between 35.6 to 35.7 from 2030 to 2070.

Sea surface temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	19.3	0.6	0.6	1.1	1.2	1.5	2.0
'Hotter and drier'	19.3	0.9	0.9	1.6	1.9	2.2	1.9
'Wetter'	19.3	1.1	1.0	1.8	2.1	2.5	3.4

Table 7. Baseline climate and projected annual sea surface temperature change (°C) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

Sea surface salinity (psu)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Wetter'	35.5	0.1	0.1	0.1	0.1	0.1	0.2

Table 8. Baseline climate and projected annual sea surface salinity change (PSU) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

3.4 Extreme weather events

Data from CSIRO is not as comprehensive for extreme weather events as the more common variables. The medium emissions scenario (A1B) was not available for the 2050s and 2070s so the low emissions scenario (B1) has been used to present a projected range. The 'most likely' model also did not provide projections for hot days and very hot days. These projections have been derived for the Sydney/Port Kembla region and the results presented here are the best available to date.

3.4.1 Hot days and very hot days

The total number of hot days, defined by the World Meteorological Organisation as "Annual count of days with maximum temperature > 35°C", is expected to increase from 6.7 to between 6.7 and 9.5 days by the 2030s. By the 2050s this increases to 14.4 days, under a high emissions scenario. Much larger increases are projected for the 2070s with a range of 18.8 to 22.1 days. For hot days during the summer months, defined here as December, January and February, the range is between 5.4 to 10.3 days for the 2030s and 6.5 to 14.6 for the 2050s. These projections will have significant consequences for operations that need to cease when temperatures exceed 35°C or indeed for workers that require more breaks.

The number of days where maximum temperatures are greater than 40°C is far less, both annually and for the summer months. Currently the number of days exceeding this temperature is 0.6 and 0.5 days respectively. By the 2050s this could reach between 0.8 and 1.9 days per year and for the 2070s, between 0.9 and 4.1 days per year.

3.4.2 Extreme precipitation

Overall, climate change projections for NSW highlight increases in the occurrence of extreme rainfall events for many parts of the state. These events are most likely to occur in summer and autumn months, with the most vulnerable regions being eastern coastal regions, and central and south-east NSW (CSIRO 2004).

3.4.3 Extreme wind speed

Extremes in wind contribute directly to hazardous conditions causing damage to the built and natural environment. They also create hazardous conditions over oceans and are responsible for the generation of storm surges and large waves which can cause coastal inundation and increase coastal erosion. Even modest changes in wind speed can alter the wave climate.

Annual days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	6.7	6.7	-	7.2	14.4	9.0	22.1
'Wetter'	6.7	9.5	-	9.7	14.4	11.1	18.8

Table 9. Baseline climate and projected days per annum over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Annual days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	0.6	0.7	-	0.8	1.8	0.9	4.1
'Wetter'	0.6	1.0	-	1.1	1.9	1.3	2.9

Table 10. Baseline climate and projected days per annum over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	5.3	5.0	-	5.4	9.7	6.5	14.6
'Wetter'	5.3	7.2	-	7.2	10.3	8.2	13.2

Table 11. Baseline climate and projected summer days over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	0.5	0.6	-	0.6	1.4	0.7	3.3
'Wetter'	0.5	0.8	-	0.8	1.5	1.0	2.3

Table 12. Baseline climate and projected summer days over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

4 BIBLIOGRAPHY

ACE CRC, 2008. *Briefing: A Post-IPCC AR4 Update on Sea-level Rise*, Hobart, Tasmania. Available at: http://www.cmar.csiro.au/sealevel/downloads/797655_16br01_slr_080911.pdf

Australian Bureau of Statistics, 2001. How many people live in Australia's coastal areas? Available at: [http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0FeatureArticle32004?opendocument&tabname=Summary&prodno=1301.0&issue=2004&num=&view=.](http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0FeatureArticle32004?opendocument&tabname=Summary&prodno=1301.0&issue=2004&num=&view=)

CSIRO, 2004. Climate Change to Increase extreme Rainfall.

CSIRO & Bureau of Meteorology, 2012. *State of the Climate*, Available at: <http://www.csiro.au/en/Outcomes/Climate/Understanding/State-of-the-Climite-2012.aspx>.

Church, J. et al., 2006. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine*, 55, pp.253–260.

Clarke, J., Whetton, P. & Hennessy, K., 2011. Providing application-specific climate projections datasets: CSIRO's Climate Futures Framework.

DCCEE, 2011. *Climate Change Risks to Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment*, Commonwealth of Australia, Canberra.

Friedlingstein, P. et al., 2010. Update on CO2 emissions. *Nature Geoscience*.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In S.

Solomon et al., eds. Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007b. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change S*. Solomon et al., eds., Cambridge, United Kingdom and New York, NY, USA.

Office of Environment and Heritage, 2011. NSW Climate. Available at: <http://www.environment.nsw.gov.au/bioregions/BioregionsNswoutlineClimate.htm>

Rahmstorf, S. et al., 2007. Recent Climate Observations Compared to Projections. *Science*, 316, p.709. Available at: http://www.pik-potsdam.de/~stefan/Publications/Nature/rahmstorf_etal_science_2007.pdf

Raupach, M.R. et al., 2007. Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 104(24), pp.10288–93. Available at: <http://www.pnas.org/cgi/content/long/104/24/10288>

Steffen, W. & Hughes, L., 2012. *The Critical Decade: New South Wales climate impacts and opportunities*,

UNEP, 2012. *GEO5: Summary for Policy Makers*, Available at:
http://www.stakeholderforum.org/fileadmin/files/GEO5_SPM_English.pdf [Accessed October 25, 2012].

Whetton, P. et al., 2012. Use of Representative Climate Futures in impact and adaptation assessment. *Climatic Change*, pp.1–10.

Climate Risk Information

Climate Change Scenarios and Implications for the Port of Gladstone

Climate Change Adaptation Program, RMIT University



Climate Risk Information

Climate Change Scenarios and Implications for the Port of Gladstone

September 2012

Lead authors

Sophie Millin, Climate Change Adaptation Program, RMIT University

Jane Mullett, Climate Change Adaptation Program, RMIT University

Acknowledgements

The content covered in this guide draws not only on direct contributions from the collaborators mentioned above but also from a range of individuals within BOM and CSIRO. The project team would like to thank the following people in the development of this guide: Leanne Webb and Penny Whetton from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Shoni Maguire from the Bureau of Meteorology (BOM). We also acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Disclaimer

The forward climate projections in this document were created with the support of the CSIRO. The Data describes possible futures. They are not predictions. Please note that any use of the Data is solely at the Recipient's own risk.

Cover photo

Aerial photograph of Port Gladstone (Image: Gladstone Ports Corporation limited)

TABLE OF CONTENTS

1	INTRODUCTION	1
1.1	Purpose of this report.....	1
1.2	The Gladstone region	1
2	OBSERVED CLIMATE IN QUEENSLAND	3
2.1	Temperature.....	3
2.2	Precipitation	4
2.3	Sea level rise	4
2.4	Extreme Weather Events.....	6
3	FUTURE CLIMATE PROJECTIONS	8
3.1	Global Climate Models, emissions scenarios and time periods	8
3.2	Atmospheric Projections	9
3.3	Ocean Projections.....	11
3.4	Extreme Weather Events.....	15
4	FURTHER READING	17

List of Figures

Figure 1	The Gladstone region within Queensland.
Figure 2	Mean minimum and mean maximum temperatures for Gladstone Radar Site
Figure 3	Average annual rainfall in Gladstone, 1957-2012
Figure 4	Trend in annual total rainfall (mm/10 years) for the 1970-2010 period.
Figure 5	Rate of sea level rise around Australia from January 1993 to December 2011.
Figure 6	The number of very hot days (days over 40°C) across Australia.
Figure 7	Occurrence of Tropical Cyclones at Port of Gladstone
Figure 8	Annual carbon emissions in billion tonnes for 1990-2010
Figure 9	Regional sea level rise projections around the Australian coastline
Figure 10	Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m.

List of Tables

Table 1	Data for mean minimum and maximum temperatures for Gladstone Radar Site
Table 2	Baseline climate and projected annual surface temperature change
Table 3	Baseline climate and projected annual precipitation change
Table 4	Baseline climate and projected annual relative humidity change
Table 5	Sea level change (m) over the 21 st century with respect to 1990.
Table 6	Components of sea level rise
Table 7	Baseline climate and projected annual sea surface temperature
Table 8	Baseline climate and projected annual sea surface salinity
Table 9	Baseline climate and projected days per annum over 35 degrees Celsius
Table 10	Baseline climate and projected days per annum over 40 degrees Celsius
Table 11	Baseline climate and projected summer days over 35 degrees Celsius
Table 12	Baseline climate and projected summer days over 40 degrees Celsius
Table 13	Baseline climate and projected annual extreme precipitation change
Table 14	Baseline climate and projected summer extreme precipitation change
Table 15	Baseline climate and projected annual extreme wind speed change

1 INTRODUCTION

This report provides information on observed climate change within Queensland and future climate projections for the Gladstone region, and the Port of Gladstone specifically.

1.1 Purpose of this report

This report has been produced to provide accessible and relevant climate information for Gladstone and Gladstone Ports Corporation, in Queensland. Both past climate observations and future climate projections are described.

The report focuses on the state of Queensland for the observed climate and the local government region of Gladstone for the future climate projections. Information has been taken from the following publicly available sources:

- Bureau of Meteorology's website on *Australian Climate Extremes*
- Gladstone Ports Corporation *Fisherman's Landing Northern Expansion EIS: Climate and Air Quality and Climate Change Assessment* (GHD, 2009)
- CSIRO and Bureau of Meteorology *Climate Change in Australia*
- CSIRO's Marine and Atmospheric Research website on *Sea Level Rise*

In producing the report the authors note that every care has been taken to produce consistent results but in some instances data was not available so other variables have been used. Where possible, this report aims

to provide a long-term view by looking to 2070 and 2100. In doing so, the authors hope that the port authorities have the resources to make more informed decisions for adapting to long-term climate change. The following areas have been looked at with respect to their potential to impact the function of the harbour authority:

- Temperature and precipitation
- Relative humidity
- Sea level rise
- Sea surface temperature and salinity
- Extreme weather events

1.2 The Gladstone region

Gladstone is situated within the Gladstone region of coastal Queensland, approximately 550 kilometres north of Brisbane, between the Rockhampton region to the north and the Bundaberg region to the south (Figure 1). The region's coastline extends from Curtis Island National Park to Long Island and Baffle Creek estuary in the south. The Regional Council of Gladstone covers an area of 10,488 square kilometres and has a population of 58,000 (ABS 2008). The region experiences a tropical savanna climate with distinct seasonal differences in rainfall patterns. The wet season, during the summer months of December, January and February, receives nearly half (47.4%) of the average annual rainfall.

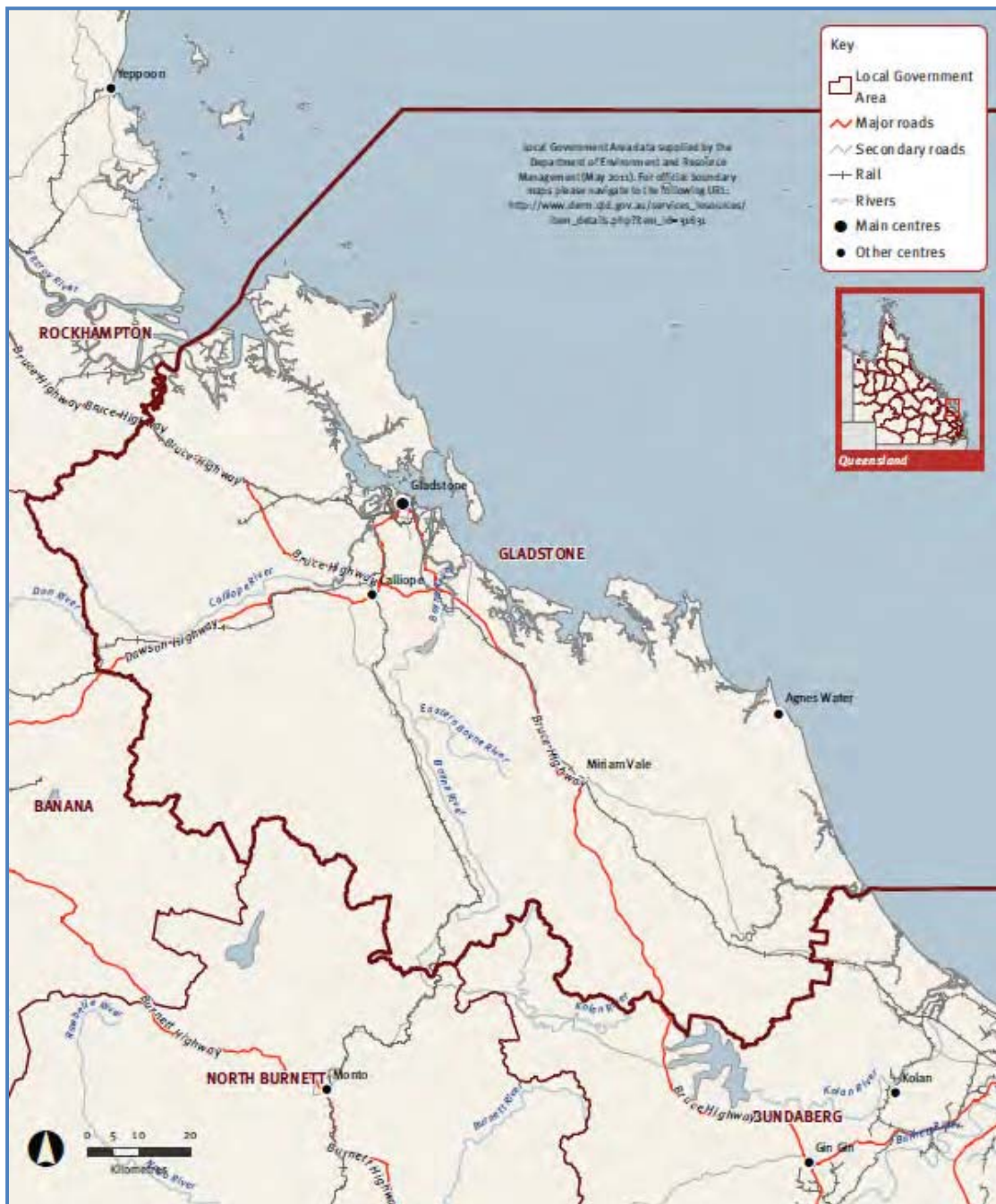


Figure 1. The Gladstone region within Queensland. Source: <http://www.dlg.qld.gov.au> © the State of Queensland (Department of Local Government and Planning) 2011.

2 OBSERVED CLIMATE IN QUEENSLAND

This section presents observed climate information for temperature, precipitation, sea level rise and extreme weather events in Gladstone.

2.1 Temperature

Air temperature data was sourced from the Bureau of Meteorology's website, using the Gladstone Radar site from the period December 1957 to January 2012.

The mean minimum and mean maximum temperatures (°C) for each month are plotted in Figure 2. Gladstone's average temperatures range from 13.4 to 22.8°C in July to 22.5 to 31.2°C in January (Table 1).

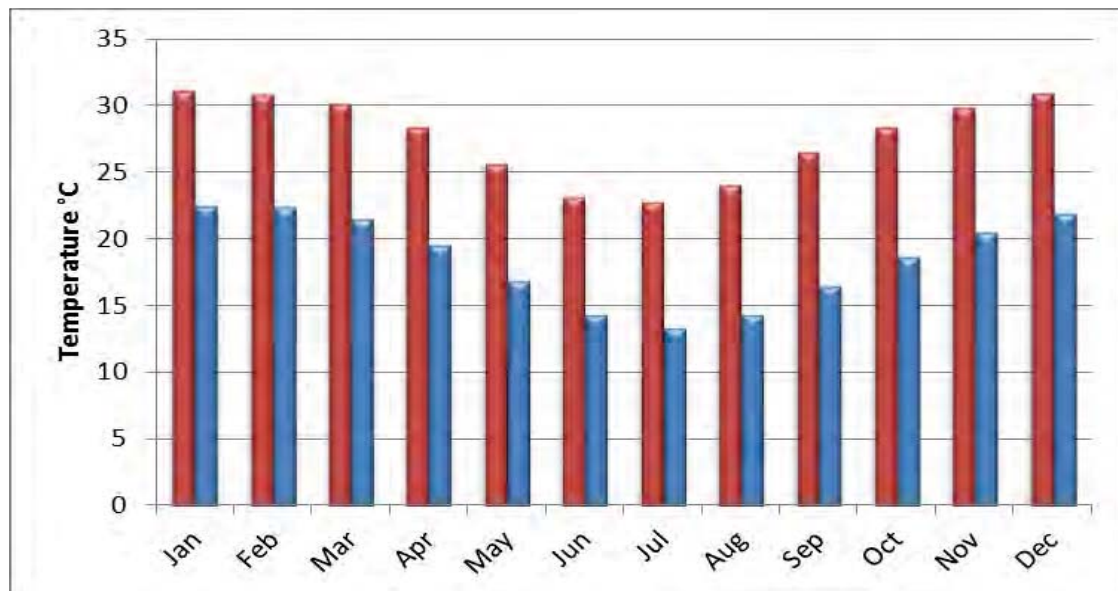


Figure 2: Mean minimum and mean maximum temperatures for Gladstone Radar Site, 1957–2012.

Source: Bureau of Meteorology.

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean max temperature (°C)	31.2	30.9	30.2	28.4	25.7	23.2	22.8	24.1	26.5	28.4	29.9	31	27.7
Mean min temperature (°C)	22.5	22.4	21.5	19.6	16.9	14.3	13.4	14.3	16.5	18.7	20.5	21.9	18.5

Table 1: Data for mean minimum and maximum temperatures for Gladstone Radar Site, 1957–2012.

Source: Bureau of Meteorology.

2.2 Precipitation

Annual average rainfall for the Gladstone Radar Site is 877 mm. There are distinct seasonal differences in rainfall patterns throughout the year with the wet season in the summer months receiving 47.4% of the annual average rainfall. Figure 3 demonstrates these seasonal differences.

The highest annual rainfall in Gladstone was 1732 mm in 1971, and the lowest annual rainfall was in 1965, measuring 432 mm.

With respect to rainfall observations for the state, Queensland has become slightly wetter over the last 110 years, apart from the coastal region stretching from the southeast northwards to Townsville. This coastal drying trend has become more obvious over the last forty years (Figure 4).

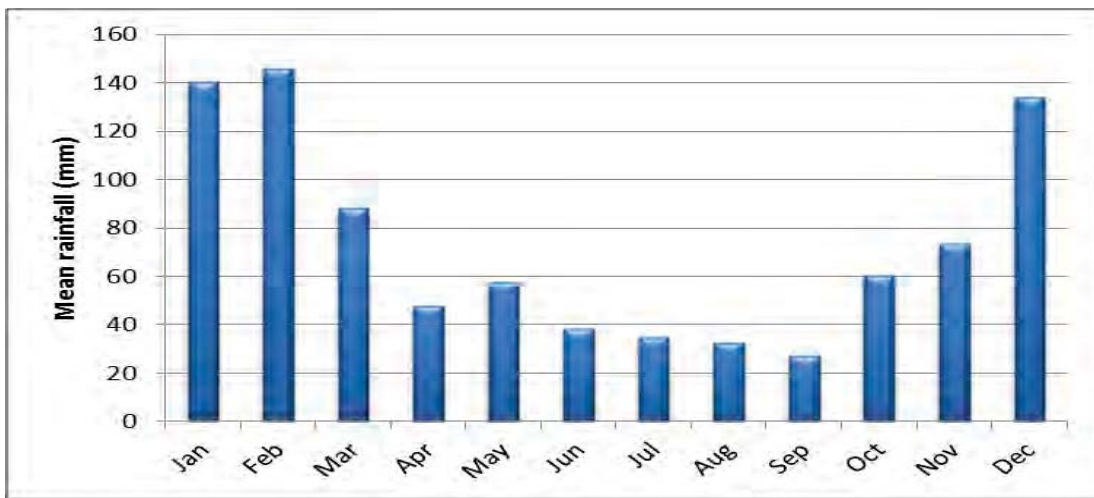
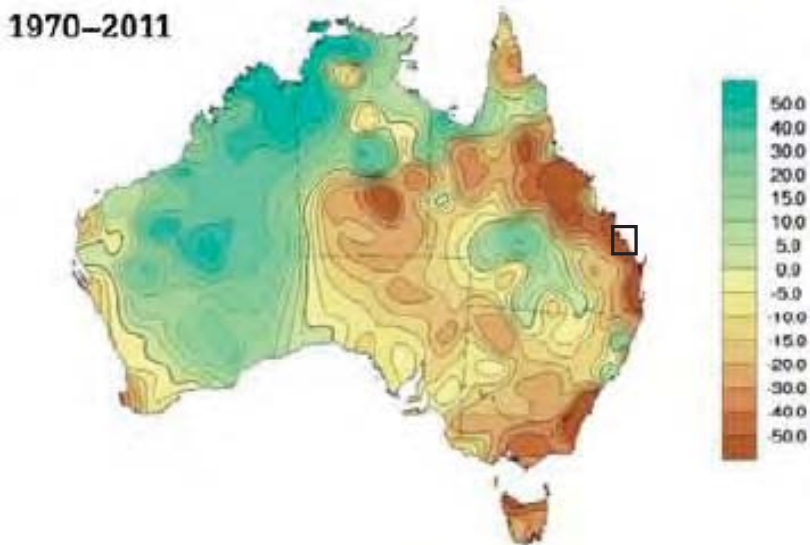


Figure 3: (Above) Average annual rainfall in Gladstone, 1957-2012 Source: Bureau of Meteorology

Figure 4. (Below) Trend in annual total rainfall (mm/10 years) for the 1970-2010 period. The Gladstone region is shown by the box. Source: Bureau of Meteorology.



2.3 Sea level rise

Globally, sea levels have risen by about 20cm since 1870. Tide gauge measurements available since the late 19th century indicate that sea levels have risen by 1.7 ± 0.3 mm/year since 1950. This figure increases from 1993 to 2011 to 3.1 ± 0.4 mm/year suggesting that sea level rise is accelerating.

Across Australia, sea levels have risen 7 to 11 mm per year in the north and northwest, two to three times the global average, whereas rates of sea-level rise on the central east and southern coasts of the continent are mostly similar to the global average (Figure 5). These regional variations are largely due to differences in the warming of the ocean waters around the coastline.

The rate of sea level rise has not been even around the world, but the average rise in eastern Australia has been between 24 and 48 millimetres since 1994, which is a rate of 1.4-2.8mm a year. Sea levels at the Port of Gladstone, just south of Rosslyn Bay, have risen at a slightly higher rate of 3mm a year.

Rising sea levels have significant repercussions for much of Queensland, where 88% of the population (3.2 million people) live within 50km of the coast (Australian Bureau of Statistics 2001). Rising sea levels pose considerable risk to coastal property, infrastructure and beaches through coastal flooding and erosion.

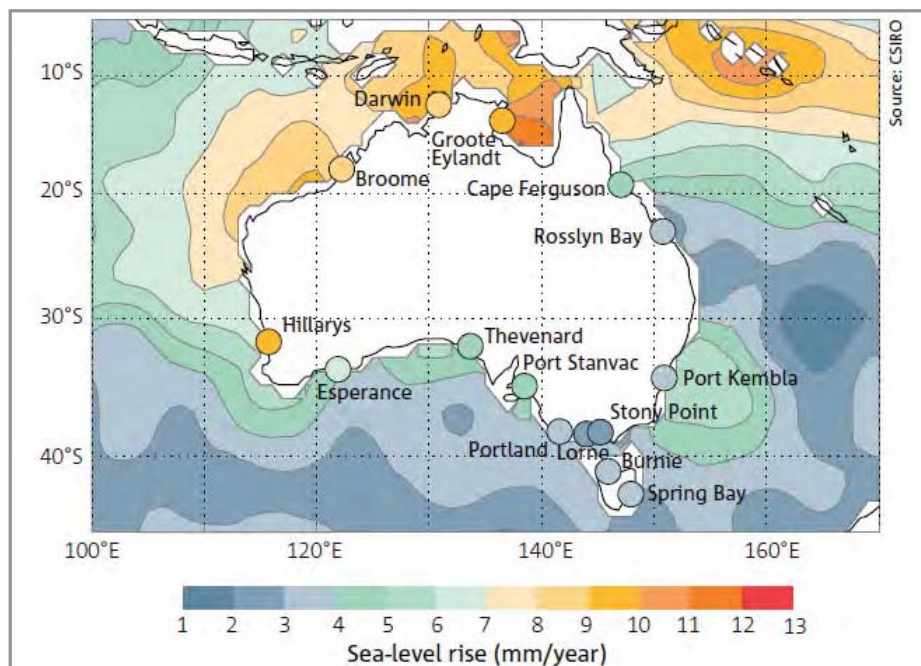


Figure 5. Rate of sea level rise around Australia as measured by coastal tide gauges (circles) and satellite observations (contours) from Jan 1993 to Dec 2011.

Source: (CSIRO & Bureau of Meteorology 2012)

2.4 Extreme weather events

The meteorological or statistical definition of extreme weather events are events at the extremes (or edges) of the complete range of weather experienced in the past. Defined in this way, extreme weather events include, but are not limited to, events like heat waves or intense rainfall.

The climate variables explained here include temperature, precipitation, wind speed and sea level rise. Each of these operates at a variety of timescales. When experienced in limited duration, they are referred to as an extreme event. A heat wave is an example of a temperature-related extreme event. For precipitation, the extreme event timescales are asymmetric; heavy precipitation events generally range from less than one hour to a few days, whereas droughts can range from months to years. And while sea level rise is a gradual process, storm surges represent

short-term high-water levels superimposed onto mean sea level. These are generally as a result of strong onshore winds and/or reduced atmospheric pressure.

2.4.1 Heat waves

Although there is no universal definition of a heat wave, it can be defined as a prolonged period of excessive heat. When using data to examine heat waves, two parameters can be used: hot days and very hot days; days that maximum temperatures exceed 35°C and 40°C, and heat waves; three consecutive days of 35°C and above.

Between 1957 and 2012, the number of hot days (days over 35°C) in Gladstone was 4.5 days per year. There were no days over 40°C but the number of days where temperatures were equal or greater than 30°C was 111.6 days per year.

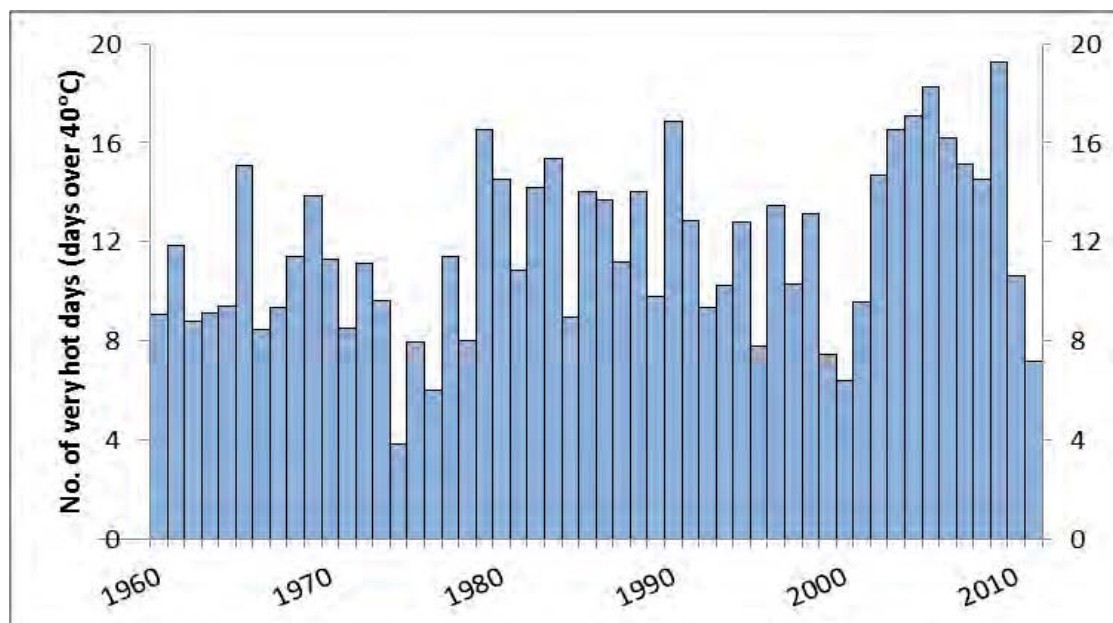


Figure 6. The number of very hot days (days over 40°C) across Australia.

Source: Bureau of Meteorology.

2.4.2 Extreme precipitation

Heavy rainfall events are a natural feature of the Queensland climate. However the prolonged and extensive rain that fell over large areas of the state in 2010/2011 caused flooding of historic proportions. Six major rain events occurred between November 2010 and January 2011, resulting in the wettest spring and the wettest December on record for Queensland. The rain was largely due to the influence of a strong La Niña event in the Pacific Ocean. The events were more notable in Queensland than other states due to the rainfall duration, rather than the daily intensity. During the rainfall, the Port of Gladstone reduced its export capacity because the coal stockpiles at the port were saturated and further coal deliveries could not be made by rail.

2.4.3 Tropical Cyclones

Tropical Cyclones are storm systems characterised by an intense low pressure centre and thunderstorms that produce strong winds and heavy rains. Most of these within the Gladstone region occur between

January and March. The Bureau of Meteorology's records show that twelve tropical cyclones passed within 100km of Gladstone between 1940 and 2006 (Figure 7). Additionally in March 2009, tropical cyclone Hamish passed along the coastline near Gladstone. Although the cyclone did not cross the coastline, the event caused the temporary closure of the Port of Gladstone (GHD 2009).

2.4.4 Storm Surge

All tropical cyclones on or near the coast are capable of producing a storm surge, which can increase coastal water levels for periods of several hours and simultaneously affect over 100 km's of coastline (Queensland Government 2004). A study on severe thunderstorms in South East Queensland (Harper & Callaghan 1998) provides a summary of recorded storm tide events within 150 km of Gladstone. It shows that at least 8 separate surge events have occurred over the past 55 years. These ranged from 0.3 to 1.2m in height and about a quarter resulted in storm tide levels reaching above the HAT (Highest Astronomical Tide) level.

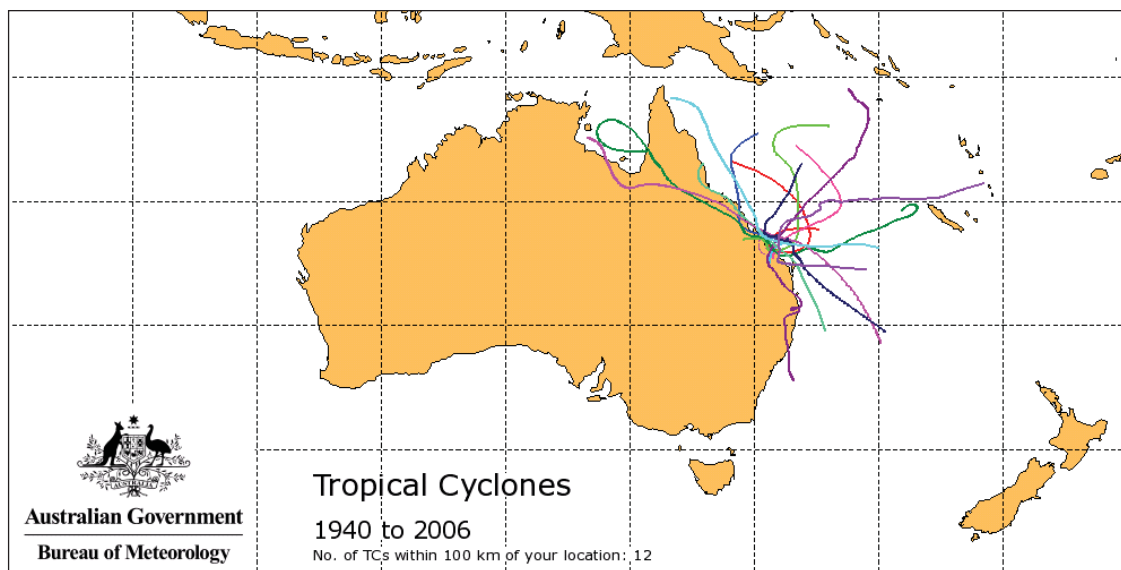


Figure 7. Occurrence of Tropical Cyclones at Port of Gladstone Source: Bureau of Meteorology

3 FUTURE CLIMATE PROJECTIONS

This section provides information on Global Climate Models, emissions scenarios and time periods. It also details future projections for atmospheric and ocean variables as well as a final section on extreme weather events.

3.1 Global Climate Models, emissions scenarios and time periods

Global climate models (GCMs) are mathematical representations of the behaviour of the planet's climate system through time. Each mathematical equation is the basis for complex computer programs used for simulating the atmosphere or oceans of the Earth. In this study, four models were selected by considering the alignment of model results over the region of Gladstone, as defined by the CSIRO's Climate Futures software (Whetton et al. 2012). 18 climate models were sub-divided into pre-defined categories such as "Hotter, Drier" and then assigned a relative likelihood based on the number of climate models that fell within that category. For example, if 9 of 18 models fell into the "Warmer – Drier" category, it was given a relative likelihood of 50% (Clarke et al. 2011). The models selected for the Port of Gladstone were:

- i. **CSIRO MK3.5** - A 'most likely'* future: hotter and little change in rainfall.
- ii. **MRI2.3.2** - A 'hot/dry' future: much hotter and much drier.
- iii. **MIROC3.2-Medres** - A 'wetter' future: cooler and wetter.
- iv. **MIROC3.2-Hires** – A 'wetter' future: slightly warmer and wetter.

*Category represented by the greatest number of models.

Modelling future climate change requires an estimation of the concentrations of greenhouse gases and other substances in the atmosphere, in the years to come. **Emissions scenarios** describe these future releases and are the product of complex dynamic systems, determined by factors such as population change, socio-economic development, and technological advances. The two emissions scenarios that were available and selected by the research team were from the 'A1 storyline' and were developed by the IPCC Special Report on Emissions Scenarios (SRES). These scenarios are labelled based on their relative greenhouse gas emissions levels, High (SRES A1FI) and Medium (SRES A1B). The team chose not to represent a Low emissions scenario (SRES B1) as much of the literature suggests this scenario may underestimate future emission scenarios (Raupach et al. 2007; Friedlingstein et al. 2010) see Figure 8.

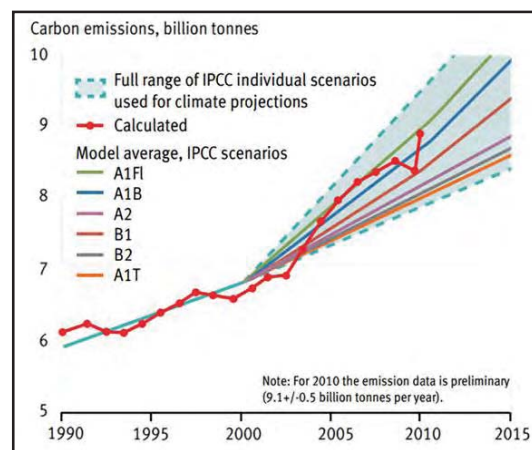


Figure 8. Annual carbon emissions in billion tonnes for 1990-2010. Source:(UNEP 2012)

GCMs project the likely range of changes over decadal to multi-decadal time periods. These **time periods** are expressed relative to the given baseline period and are centred on a given decade. So, the 2050s time period refers to the period 2040-2069. Thirty year time periods provide an average over this range, cancelling out much of the random year-to-year variability. This study focuses on three time periods; the 2030s, 2050s and 2070s.

3.2 Atmospheric projections

The results presented in this section (Tables 2, 3 and 4) show the projected change from the 1975-2004 baseline climate. Data is provided for three time periods and for three models. The 'wetter' model in these projections is based on the MIROC3.2-Medres model. The range shown is from the medium (A1B) to the high (A1FI) emissions scenario.

3.2.1 Temperature

Annual mean temperature projections for the Port of Gladstone (Table 2) show that there is likely to be a slight increase by the 2030s, with a projected increase of 0.7 to 0.9 degrees Celsius (°C) above 1975-2004 values, across the three models. By the 2050s this increases to 1.2 to 2.1°C. Larger ranges are projected for the 2070s, with increases from 1.5 to 2.9°C above the baseline climate. For the Port of Gladstone, annual mean temperatures may increase from 22.2°C to between 23.4 and 24.3°C in the 2050s, and to between 23.7 and 25.1°C by the 2070s. Despite temperature increases for the 2030s being relatively modest, a small increase in mean temperature can lead to a large increase in the frequency and severity of extreme heat events. There is also not a large distinction

between the emissions scenarios until after the 2030s as temperature patterns do not distinguish from each other until after this period. This is due to the time it takes for each emissions scenario to produce large differences in greenhouse gas concentrations.

3.2.2 Precipitation

Rainfall in coastal regions is difficult to simulate due to changes in weather patterns that cannot be resolved by climate models. This creates a large range of uncertainty for precipitation projections (Table 3). Both the 'most likely' model and the 'hotter and drier' model show a definite drying trend, which increases across the three time periods, whereas the 'wetter' model projects increases in rainfall. To gain more certainty in the projections requires seasonal projections which the *Gladstone Ports Corporation Climate Change Assessment* (GHD 2009) has examined. This suggests that for the 2030s, the Gladstone region is likely to experience a slight decrease in summer and winter rainfall and by the 2070s this reduction increases with a projected change of -21.5% and -41.8% for summer and winter rainfall respectively.

3.2.3 Relative humidity

Relative humidity projections show decreases for all time periods for the 'most likely' and 'hotter and drier' models (Table 4) which reflect the average projections across Australia. For the 2030s, the 'most likely' model ranges from -0.7 to -0.6% change. By the 2050s, this range increases to -1.2 to -1.5% and by the 2070s the reductions are between -1.6 and -2.1% change. The 'hotter and drier' model projects very similar results.

Temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	22.2	0.9	0.9	1.7	2.1	2.1	2.9
'Hotter and drier'	22.2	0.7	0.6	1.2	1.5	1.5	2.1
'Wetter'	22.2	0.8	0.8	1.5	1.9	1.9	2.6

Table 2. Baseline climate and projected annual surface temperature change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Precipitation (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	850	-1.9	-1.8	-3.5	-4.4	-4.5	-6.1
'Hotter and drier'	850	-10.6	-10.1	-19.8	-24.6	-20.7	-34.1
'Wetter'	850	2.2	2.2	4.2	5.2	5.3	7.2

Table 3. Baseline climate and projected annual precipitation change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Relative Humidity (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	76.3	-0.7	-0.6	-1.2	-1.5	-1.6	-2.1
'Hotter and drier'	76.3	-0.6	-0.6	-1.1	-1.4	-1.4	-2.0
'Wetter'	76.3	0.4	0.4	0.8	1.0	1.1	1.4

Table 4. Baseline climate and projected annual relative humidity change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

3.3 Ocean projections

3.3.1 Sea-level rise

Mean sea level rise occurs due to two main processes; the melting of land based ice, which increases the mass of the ocean, and decreases in ocean density, which increases the volume of the ocean. The latter mainly occurs due to increases in the heat content of the oceans which is referred to as thermal expansion.

The IPCCs Fourth Assessment Report (IPCC 2007) projects global mean sea level rise at between 0.21 and 0.59m for the medium and high emissions scenario. Concerns that these projections may have been underestimated (Rahmstorf et al. 2007) have led CSIRO's Centre for Marine and Atmospheric Research (CMAR) to produce updated figures. These projections are based on outputs from the

climate models and include changes in ocean temperature used to estimate changes in sea level due to thermal expansion and estimated flow rates from Greenland and Antarctica (Table 5). The figures show a projected global sea level rise of between 0.22 and 0.81m for the medium and high emission scenario.

As sea levels do not rise uniformly around the globe, regional variations need to be taken into account. Figure 9 shows projections around the Australian coastline. The top panel shows the difference between projected sea level and the global average with the average of all the models shown with the heavy blue line. The bottom panel allows for the identification of regional sea level rise projections at specific locations around the coastline. Each number corresponds with the top panel numbers.

	Medium			High		
	5th percentile	Central estimate	95th percentile	5th percentile	Central estimate	95th percentile
1990	0	0	0	0	0	0
2000	0.01	0.02	0.03	0.01	0.02	0.03
2010	0.02	0.04	0.06	0.02	0.04	0.06
2020	0.04	0.07	0.09	0.04	0.07	0.1
2030	0.06	0.1	0.14	0.06	0.1	0.14
2040	0.08	0.14	0.19	0.08	0.14	0.20
2050	0.1	0.18	0.25	0.1	0.18	0.27
2060	0.12	0.22	0.32	0.13	0.24	0.35
2070	0.15	0.27	0.39	0.16	0.31	0.45
2080	0.17	0.32	0.47	0.19	0.38	0.56
2090	0.19	0.37	0.55	0.23	0.45	0.68
2100	0.22	0.43	0.64	0.27	0.54	0.81

Table 5: Global sea level change (m) over the 21st century, including rapid ice sheet melt, with respect to 1990. The figures shown are for the medium (A1B) and high (A1FI) emissions scenarios, with 5th to 95th percentile confidence intervals. Figures are based on methods outlined in the IPCC's Fourth Assessment Report (Meehl et al. 2007). Source: http://www.cmar.csiro.au/sealevel/sl_proj_21st.html

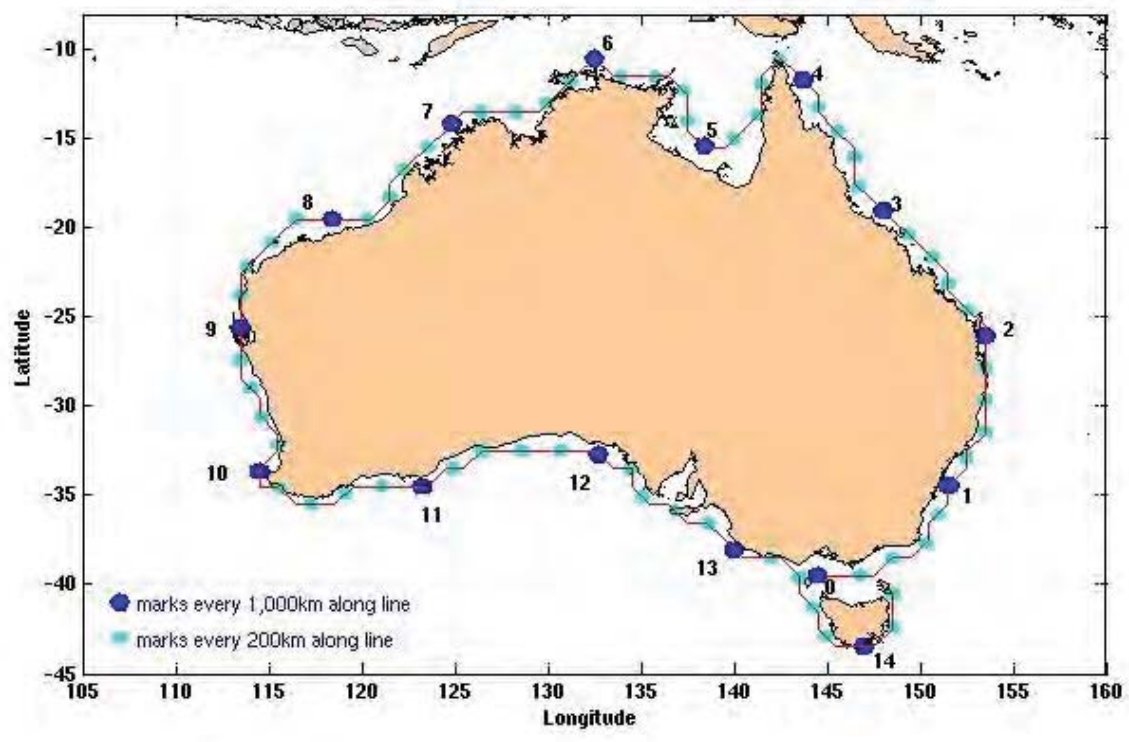
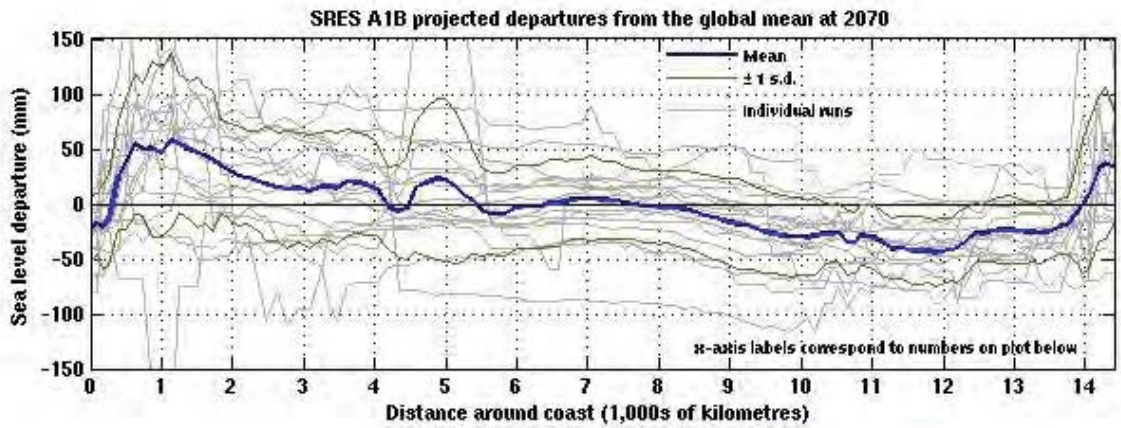


Figure 9: Regional sea level rise projections around the Australian coastline. Figures are derived from the 2070 globally-averaged mean projections for the A1B SRES scenario Source: http://www.cmar.csiro.au/sealevel/sl_proj_regional.html

Table 6 shows projections for global sea level rise together with regional projections taken from Figure 9 at 2361 kilometres around the coastline or approximately two turquoise dots north of point 2. This is the location closest to the latitude and longitude of the Port of Gladstone.

The sea level rise projections for the Port of Gladstone in 2030 and 2070 are 15.2 and 47.1cm respectively. It should be noted that sea levels will continue to rise after 2070 and long-term planning should take into account projections after this date.

Component	2030	2070
Sea level rise (m) taken from high emission scenario (Table 5)	0.14m	0.39m
Regional sea level rise variation	0.0115m	0.0205m
Total	0.152m (15.2cm)	0.4105m (41cm)

Table 6: Components of sea level rise including CSIRO's updated CMAR figures together with regional projections derived from the global average (see Figure 9).

Sea-level rise will create risk to properties, infrastructure and beaches along the coastal areas of Queensland. The main threats from sea-level rise will include:

1. Storm-related flooding
2. Flooding from higher sea levels
3. Erosion of the land

1. Storm surge flooding

During severe storm events the impacts of sea-level rise are more apparent. When a storm event coincides with a storm surge and high tide, small rises in sea level can result in very large increases in the frequency of coastal flooding (ACE CRC 2008; J. Church et al. 2006). This increases the risk of flooding to property, infrastructure and beaches. North Queensland, in particular, is vulnerable to coastal flooding, as more intense tropical cyclones could drive very large storm surges as well as heavy rainfall. Flooding caused by a combination of a high tide, a storm surge and rising sea-level is often called a 'high sea-level event'

2. Flooding from higher sea levels

Figure 10 shows that a thousand-fold increase in high sea-level events means that

flooding that currently occurs only once in 100 years could occur almost every month (Figure 10).

3. Erosion

Higher sea levels can cause erosion of beaches, and the retreat of soft coastlines further inland. Long stretches of sandy beaches in southeast Queensland – the Gold Coast, Moreton Bay, Brisbane and the Sunshine Coast – are threatened by the increased coastal erosion resulting from rising sea levels.

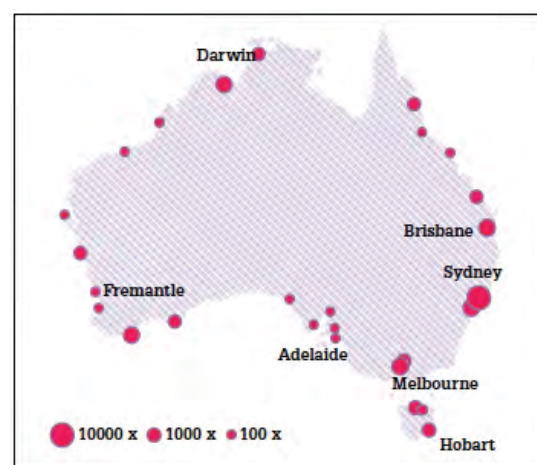


Figure 10. Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m. Source ACE CRC 2008.

3.3.2 Ocean temperature and salinity

This section considers the temperature of the sea surface (or sea-surface temperature - SST) and sea-surface salinity (SSS). As before, projections are derived for three 30-year time periods centred on 2030, 2050 and 2070, relative to the 1975 to 2004 baseline. The research team aimed to keep all of the variables consistent, however, the MIROC3.2 Medres model was not available for sea surface temperature and only 'wetter' models were available for salinity. The MIROC3.2-Hires model therefore replaces the MIROC3.2 Medres model in the sea

surface temperature results and is the only model used in the salinity results.

Sea-surface temperatures for the Port Gladstone region are projected to increase by 0.5 to 1.0°C for the 2030s, 0.9 to 1.9°C for the 2050s and 1.3 to 3.1°C for the 2070s.

Sea-surface salinity (SSS) is the measure of the concentration of dissolved salt in the sea water, at, or very close to the ocean surface. Sea-surface salinity projections show no significant change with an increase in practical salinity units (psu) from 35.3 to between 35.4 and 35.5 from 2030 to 2070.

Sea surface temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	23.2	0.8	0.7	1.3	1.5	1.8	2.5
'Hotter and drier'	23.2	0.5	0.5	0.9	1.1	1.3	1.7
'Wetter'	23.2	1.0	0.9	1.6	1.9	2.3	3.1

Table 7. Baseline climate and projected annual sea surface temperature change (°C) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

Sea surface salinity (psu)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Wetter'	35.3	0.1	0.1	0.1	0.1	0.1	0.2

Table 8. Baseline climate and projected annual sea surface salinity change (PSU) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

3.4 Extreme weather events

Data from CSIRO is not as comprehensive for extreme weather events as for the more common variables. The medium emissions scenario (A1B) was not available for the 2050s and 2070s so the low emissions scenario (B1) has been used to present a projected range. The ‘hotter and drier’ model also did not provide projections for hot days and very hot days. These projections have been derived for the Gladstone region and the results presented here are the best available to date.

3.4.1 Hot days and very hot days

The total number of hot days, defined by the World Meteorological Organisation as “Annual count of days with maximum temperature > 35°C”, is expected to increase from 2.4 to between 5.0 and 5.3 days by the 2030s. Looking at only the high emissions scenario, projections for the 2050s increase to between 14.4 to 21.8 days, and for the 2070s, to between 27.6 to 42.7 days. This is almost double the number of hot days in twenty years which points to a rapid change. For hot days in the 2050s, during the summer months, (defined here as December, January and February), the range is between 11.1 and 17.3 days. This increases to between 20.5 and 32.1 days for the 2070s. These projections will have significant consequences for operations that need to cease when temperatures exceed 35°C or indeed for workers that require more breaks.

The number of days where maximum temperatures are greater than 40°C is far less, both annually and for the summer months. Currently the baseline number of

days exceeding this temperature is 0. Annually, this could reach 0.1 days for the 2050s and between 0.2 and 0.4 days for the 2070s.

3.4.2 Extreme precipitation

Climate projections show an increase in daily precipitation intensity and an increase in the number of dry days. This suggests that Queensland’s rainfall patterns will have longer dry spells interrupted by heavier rainfall events.

3.4.3 Tropical cyclones

Projected changes in tropical cyclones are subject to the source of uncertainty inherent in climate change projections. However, it is likely (with more than 66 per cent probability) that, on average, there will be fewer tropical cyclones in the Australian region but the proportion of intense cyclones is expected to increase (CSIRO & Bureau of Meteorology 2012). Some studies also report a poleward extension of tropical cyclone tracks. There is also evidence that the peak intensity may increase by 5 to 10% and precipitation rates may increase by 20 to 30%.

Intense cyclones bring very destructive winds, the extent of which will vary between cyclones. Extremes in wind contribute directly to hazardous conditions causing damage to the built and natural environment. They also create hazardous conditions over oceans and are responsible for the generation of storm surges and large waves which can cause coastal inundation and increase coastal erosion. Even modest changes in wind speed can alter the wave climate.

Annual days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Most likely'	2.4	5.3	-	5.8	21.8	9.0	42.7
'Wetter'	2.4	5.0	-	5.4	14.4	7.4	27.6

Table 9. Baseline climate and projected days per annum over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Annual days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Most likely'	0.0	0.0	-	0.1	0.1	0.1	0.4
'Wetter'	0.0	0.0	-	0.0	0.1	0.0	0.2

Table 10. Baseline climate and projected days per annum over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Most likely'	1.9	4.3	-	4.8	17.3	7.5	32.1
'Wetter'	1.9	4.0	-	4.4	11.1	5.9	20.5

Table 11. Baseline climate and projected summer days over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Most likely'	0.0	0.0	-	0.0	0.0	0.1	0.3
'Wetter'	0.0	0.0	-	0.0	0.1	0.0	0.2

Table 12. Baseline climate and projected summer days over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

4 BIBLIOGRAPHY

- ABS, 2008. Regional Population Growth, Australia, 2008-09. Available at:
<http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02008-09?OpenDocument>
- ACE CRC, 2008. *Briefing: A Post-IPCC AR4 Update on Sea-level Rise*, Hobart, Tasmania.
- Australian Bureau of Statistics, 2001. How many people live in Australia's coastal areas? (Feature Article). Available at:
<http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0FeatureArticle32004?opendocument&tabname=Summary&prodno=1301.0&issue=2004&num=&view=>
- CSIRO & Bureau of Meteorology, 2012. *State of the Climate*, Available at:
<http://www.csiro.au/en/Outcomes/Climate/Understanding/State-of-the-Climite-2012.aspx>.
- Church, J. et al., 2006. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine*, 55, pp.253–260.
- Clarke, J., Whetton, P. & Hennessy, K., 2011. Providing application-specific climate projections datasets: CSIRO's Climate Futures Framework.
- Friedlingstein, P. et al., 2010. Update on CO2 emissions. *Nature Geoscience*. Available at:
<http://www.nature.com/ngeo/journal/v3/n12/pdf/ngeo1022.pdf>
- GHD, 2009. *Report for Fishermans Landing Northern Expansion Climate Change Assessment*, Available at:
http://www.gpcl.com.au/Portals/0/pdf/Current_Projects/Fishermans_Landing_Northern_Expansion_EIS/Appendix_I.pdf
- Harper, B.A. & Callaghan, J., 1998. Modelling of severe thunderstorms in South East Queensland. In *Proceedings of the Sixth Australian Severe Storms Conference*. Brisbane.
- IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* S. Solomon et al., eds., Cambridge, United Kingdom and New York, NY, USA.
- Queensland Government, 2004. *Queensland Climate Change and Community Vulnerability to Tropical Cyclones: Synthesis Report*, Available at:
<http://www.longpaddock.qld.gov.au/about/publications/pdf/climatechange/vulnerabilitytotropicalcyclones/synthesisreport/FullReportLowRes.pdf>
- Rahmstorf, S. et al., 2007. Recent Climate Observations Compared to Projections. *Science*, 316, p.709.
- Raupach, M.R. et al., 2007. Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 104(24), pp.10288–93.

UNEP, 2012. *GEO5: Summary for Policy Makers*, Available at:
http://www.stakeholderforum.org/fileadmin/files/GEO5_SPM_English.pdf

Whetton, P. et al., 2012. Use of Representative Climate Futures in impact and adaptation assessment. *Climatic Change*, pp.1–10. Available at:
<http://link.springer.com/article/10.1007/s10584-012-0471-z/fulltext.html>

Climate Risk Information

Climate Change Scenarios and Implications for Port Kembla

Climate Change Adaptation Program, RMIT University



Climate Risk Information

Climate Change Scenarios and Implications for Port Kembla

September 2012

Lead authors

Sophie Millin, Climate Change Adaptation Program, RMIT University

Jane Mullett, Climate Change Adaptation Program, RMIT University

Acknowledgements

The content covered in this guide draws not only on direct contributions from the collaborators mentioned above but also from a range of individuals within BOM and CSIRO. The project team would like to thank the following people in the development of this guide: Leanne Webb and Penny Whetton from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Shoni Maguire from the Bureau of Meteorology (BOM). We also acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Disclaimer

The forward climate projections in this document were created with the support of the CSIRO. The Data describes possible futures. They are not predictions. Please note that any use of the Data is solely at the Recipient's own risk.

Cover photo

Aerial photograph of Port Kembla (Image credit: Port Kembla Port Corporation)

TABLE OF CONTENTS

1	INTRODUCTION	1
1.1	Purpose of this report.....	1
1.2	Port Kembla and the Illawarra region	1
2	OBSERVED CLIMATE IN NEW SOUTH WALES	2
2.1	Temperature.....	2
2.2	Precipitation	4
2.3	Sea level rise	5
2.4	Extreme Weather Events.....	5
3	FUTURE CLIMATE PROJECTIONS	8
3.1	Global Climate Models, emissions scenarios and time periods	8
3.2	Atmospheric Projections	9
3.3	Ocean Projections.....	11
3.4	Extreme Weather Events.....	15
4	FURTHER READING	17

List of Figures

Figure 1	The Illawarra region within New South Wales.
Figure 2	NSW annual mean surface temperature anomaly, 1910–2011
Figure 3	Average annual rainfall in NSW, 1900-2011
Figure 4	Trend in annual total rainfall (mm/10 years) for the 1970-2010 period.
Figure 5	Rate of sea level rise around Australia from January 1993 to December 2011.
Figure 6	The number of very hot days (days over 40°C) across Australia.
Figure 7	Storm brewing over Port Kembla, December 2011
Figure 8	Annual carbon emissions in billion tonnes for 1990-2010.
Figure 9	The spatial pattern of thermal expansion around east coast Australia
Figure 10	Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m.

List of Tables

Table 1	20 Warmest years in NSW (relative to 1961–1990) since 1910
Table 2	Baseline climate and projected annual surface temperature change
Table 3	Baseline climate and projected annual precipitation change
Table 4	Baseline climate and projected annual relative humidity change
Table 5	Sea level change (m) over the 21 st century with respect to 1990.
Table 6	Components of sea level rise
Table 7	Baseline climate and projected annual sea surface temperature
Table 8	Baseline climate and projected annual sea surface salinity
Table 9	Baseline climate and projected days per annum over 35 degrees Celsius
Table 10	Baseline climate and projected days per annum over 40 degrees Celsius
Table 11	Baseline climate and projected summer days over 35 degrees Celsius
Table 12	Baseline climate and projected summer days over 40 degrees Celsius
Table 13	Baseline climate and projected annual extreme precipitation change
Table 14	Baseline climate and projected summer extreme precipitation change
Table 15	Baseline climate and projected annual extreme wind speed change

1 INTRODUCTION

This report provides information on observed climate change within New South Wales and future climate projections for the Illawarra region, and Port Kembla specifically within New South Wales.

1.1 Purpose of this report

This report has been produced to provide accessible and relevant climate information for Port Kembla Port Corporation, in New South Wales. Both past climate observations and future climate projections are described.

The report focuses on the state of New South Wales for the observed climate and the local government region of Illawarra for the future climate projections. Information has been taken from the following publicly available sources:

- Bureau of Meteorology's website on *Australian Climate Extremes*
- NSW Government reports on *Observed Changes in New South Wales climate 2010* and *New South Wales Climate Impacts Profile*
- CSIRO and Bureau of Meteorology *Climate Change in Australia*
- CSIRO's Marine and Atmospheric Research website on *Sea Level Rise*

In producing the report the authors note that the NSW Government reports only project as far forward as 2050. This report draws on these reports and also aims to provide a longer term view by looking to 2070 and 2100. In doing so, the authors hope that the port authorities have the resources to make

more informed decisions for adapting to long-term climate change. The following areas have been looked at with respect to their potential to impact the function of the harbour authority:

- Temperature and precipitation
- Relative humidity
- Sea level rise
- Sea surface temperature and salinity
- Extreme weather events

1.2 Port Kembla and the Illawarra region

Port Kembla sits within the Illawarra region of NSW, south of Sydney and the regional city of Wollongong (Figure 1). With a population of 292,190 (Department of Planning and Infrastructure 2012), the Illawarra region is the fourth major population centre of NSW. The region has a mostly cool temperate climate, with an average annual rainfall slightly under 1100 mm (Department of Environment Climate Change and Water 2010). Rainfall is nearly uniformly distributed throughout the year with slight summer-autumn dominance. The highest rainfall occurs to the east of the steep escarpment, south of Wollongong, with an average annual rainfall of over 1600 mm.

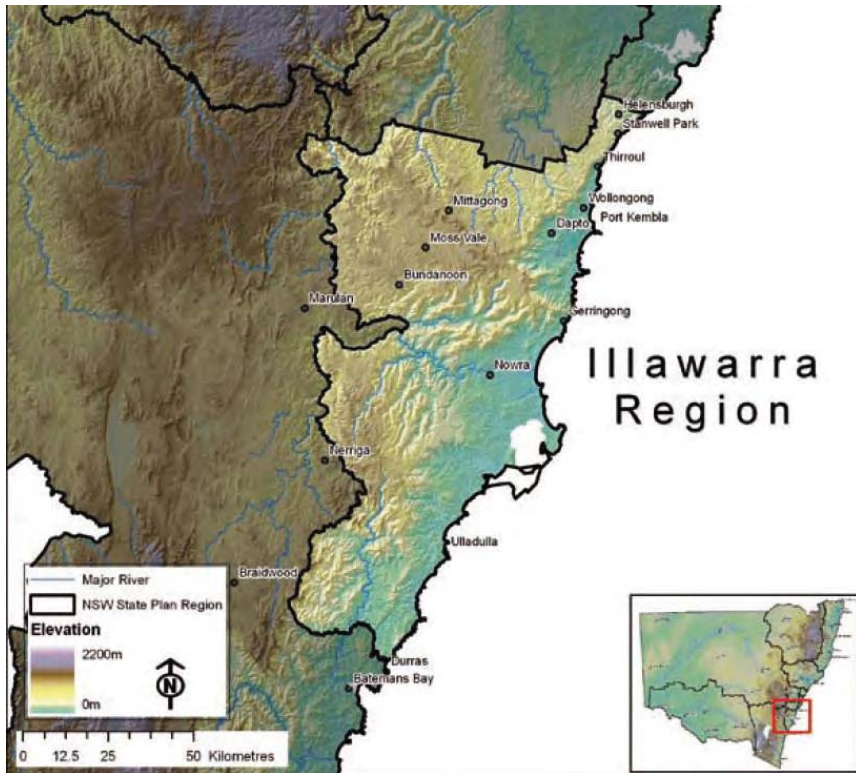


Figure 1. The Illawarra region within New South Wales. Source: www.environment.nsw.gov.au

© State of NSW and Department of Environment, Climate Change and Water NSW.

2 OBSERVED CLIMATE IN NEW SOUTH WALES

This section presents observed climate information for temperature, precipitation, sea level rise and extreme events in New South Wales.

2.1 Temperature

New South Wales (NSW) is described as having a temperate climate with warm summers and cool winters, although the climate undergoes large variations depending on the proximity to the coast and mountains

(Office of Environment and Heritage 2011). Records show an annual average air temperature of 17.3°C from 1961 to 1990. This average has been increasing at an accelerating rate since the mid-1990s, based on current climate trends (Figure 2).

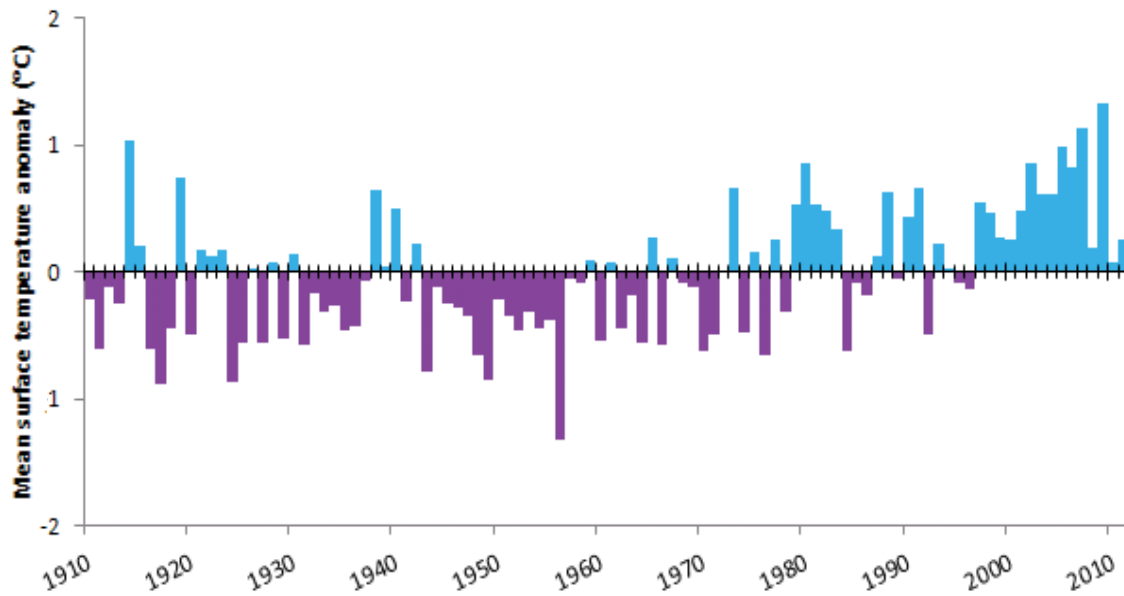


Figure 2: NSW annual mean surface temperature anomaly, 1910–2011 Source: Bureau of Meteorology.

Ranking	Year	Temperature difference	Ranking	Year	Temperature difference
1	2009	+1.33	11	1938	+0.65
2	2007	+1.13	12	1988	+0.63
3	1914	+1.04	13	2003	+0.61
4	2005	+0.99	14	2004	+0.61
5	1980	+0.86	15	1997	+0.55
6	2002	+0.85	16	1979	+0.54
7	2006	+0.83	17	1981	+0.54
8	1919	+0.75	18	1940	+0.5
9	1991	+0.67	19	1982	+0.49
10	1973	+0.66	20	2001	+0.49

Table 1: 20 Warmest years in NSW (relative to 1961–1990) since 1910. Source: Bureau of Meteorology.

2.2 Precipitation

Annual rainfall in NSW has been highly variable. There have been very dry years (such as 1940 and 2002) and very wet years (such as 1950, 1974 and recently in 2010) and generally these correlate with the dry El Nino years and wet La Nina years. With respect to the average rainfall for NSW, the

past 50 years has seen a slight decline compared with the very wet years of the 1950s (Figure 3). However, since the beginning of the 20th century, NSW as a whole has not seen an overall downward trend in rainfall. Figure 4 shows how the NSW coast and the Illawarra region in particular, has experienced a drying trend over the past 40 years.

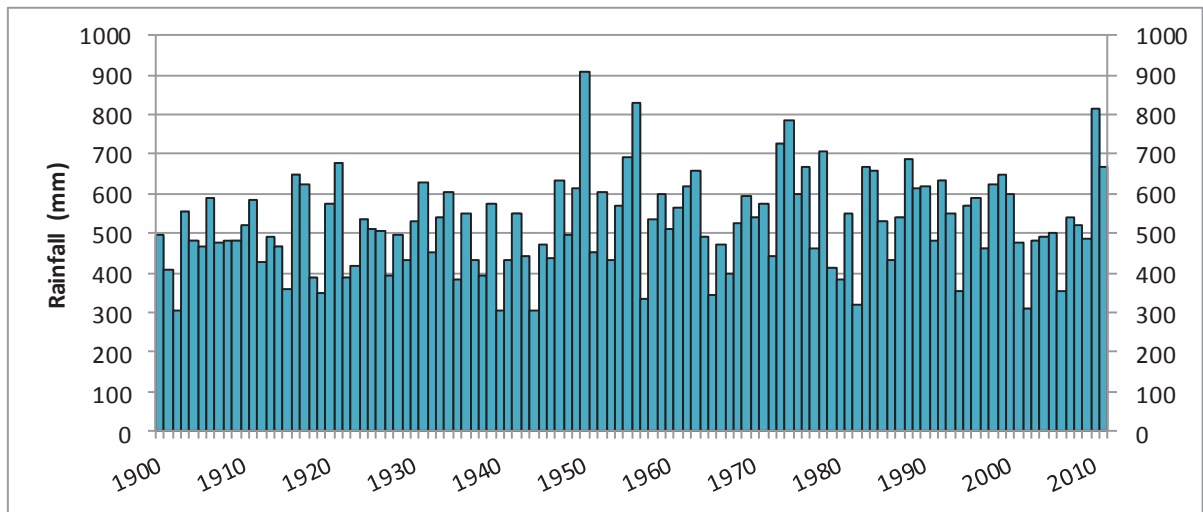
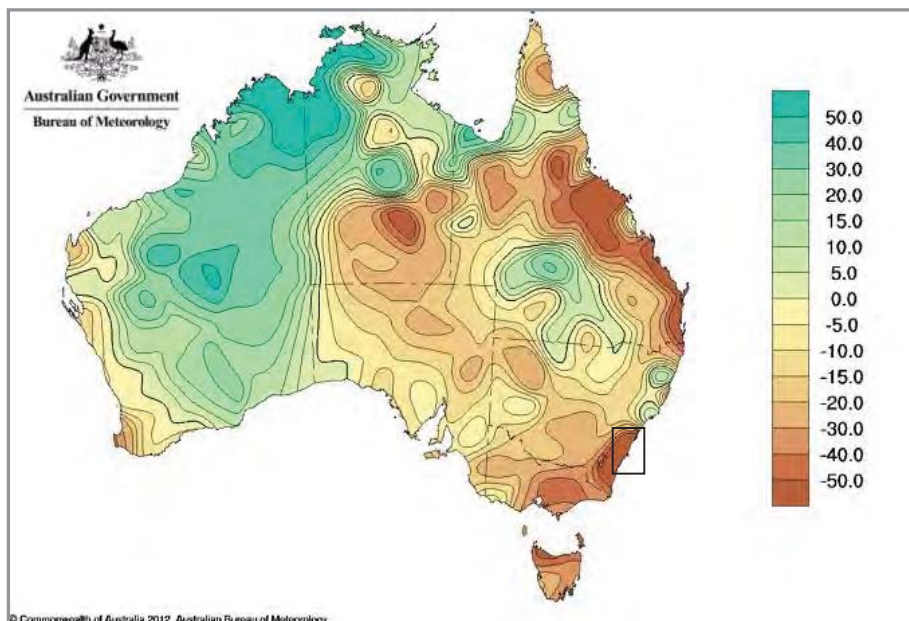


Figure 3: (Above) Average annual rainfall in NSW, 1900-2011 Source: Bureau of Meteorology.

Figure 4. (Below) Trend in annual total rainfall (mm/10 years) for the 1970-2010 period. The Illawarra region is shown by the box. Source: Bureau of Meteorology.



2.3 Sea level rise

Globally, sea levels have risen by about 20cm since 1870. Tide gauge measurements available since the late 19th century indicate that sea levels have risen by 1.7 ± 0.3 mm/year since 1950. This figure increases from 1993 to 2011 to 3.1 ± 0.4 mm/year suggesting that sea level rise is accelerating.

Across Australia, sea levels have risen 7 to 11 mm per year in the north and northwest, two to three times the global average, whereas rates of sea-level rise on the central east and southern coasts of the continent are mostly similar to the global average (Figure 5). These regional variations are largely due to differences in the warming of the ocean waters around the coastline.

The rate of sea level rise has not been even around the world, but the average rise in eastern Australia has been between 24 and 48 millimetres since 1994, which is a rate of 1.4-2.8mm a year. Sea level at Port Kembla has risen about 60 millimetres since 1991 which is a slightly higher rate of 3mm a year.

Rising sea levels have significant repercussions for much of NSW, where 85% of the population live within 50km of the coastline (Australian Bureau of Statistics 2001). High tide events give some indication of what the impacts of sea level rise could mean. A high tide in Sydney, in 2009, resulted in sea water encroaching onto roads and approaching houses. Flooding in estuaries and some coastal lakes will be exacerbated by higher sea levels.

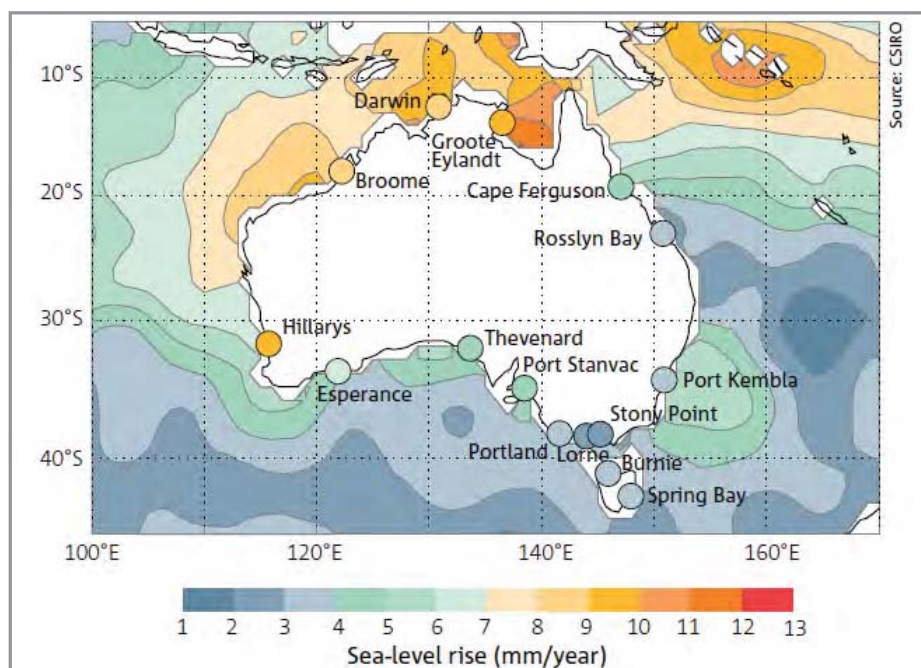


Figure 5. Rate of sea level rise around Australia as measured by coastal tide gauges (circles) and satellite observations (contours) from Jan 1993 to Dec 2011.

Source: (CSIRO & Bureau of Meteorology 2012)

2.4 Extreme weather events

The meteorological or statistical definition of extreme weather events are events at the extremes (or edges) of the complete range of weather experienced in the past. Defined in this way, extreme weather events include, but are not limited to, events like heat waves or intense rainfall.

The climate variables explained here include temperature, precipitation, wind speed and sea level rise. Each of these operates at a variety of timescales. When experienced in limited duration, they are referred to as an extreme event. A heat wave is an example of a temperature-related extreme event. For precipitation, the extreme event timescales are asymmetric; heavy precipitation events generally range from less than one hour to a few days, whereas droughts can range from months to years. And while sea level rise is a gradual process, storm surges represent short-term high-water levels superimposed onto mean sea level. These are generally as a

result of strong onshore winds and/or reduced atmospheric pressure.

2.4.1 Heat waves

Although there is no universal definition of a heat wave, it can be defined as a prolonged period of excessive heat. When using data to examine heat waves, two parameters can be used: hot days and very hot days; days that maximum temperatures exceed 35°C and 40°C, and heat waves; three consecutive days of 35°C and above.

Between 1970 and 2011, the number of hot days (days over 35°C) in NSW increased, in some areas by up to 7.5 days per decade. The number of heat waves in a given year is highly variable. For example, in 2009, NSW experienced three heat waves in January, August and November with temperatures exceeding 37 degrees. However in 2010, maximum temperatures were the coolest since 1992 at 0.47 °C below the 1961-1990 average.

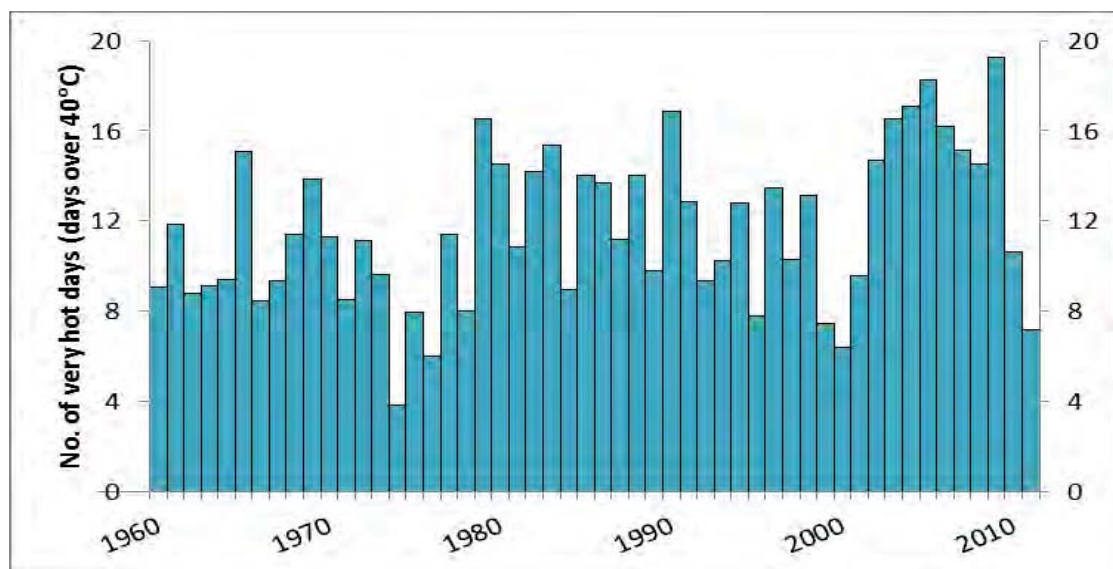


Figure 6. The number of very hot days (days over 40°C) across Australia.

Source: Bureau of Meteorology.

2.4.2 Extreme precipitation

From 1950 to 2005, extreme daily rainfall intensity and frequency increased in north-western and central Australia and over the western tablelands of New South Wales, but decreased in the south, south-east, south-west and along the central east coast (IPCC 2007).

Most recently, New South Wales experienced widespread and persistent heavy rainfall in both February 2011 and March 2012. Both of these events were associated with strong La Niña conditions which generally result in above average rainfall across eastern and northern Australia. The total rainfall recorded for March 2012 was 119.59mm, more than half the average for NSW, making 2012 the second wettest March since 1956.

In the Illawarra region the most significant rainfall events were in August 1998 and October 1999. The rain that fell between the 17th and 19th of August 1998 was the result of a stationary storm persisting over the Illawarra region. Wollongong University received 316mm of rain in 24 hours. Nearby Mt Ousley received 445mm of rain during the same period.

2.4.3 East Coast Lows

East Coast Lows (ECL) are intense low-pressure systems which occur on average ten times a year off the eastern coast of Australia. Although they can occur at any time of the year, they are more common

during Autumn and Winter with a maximum frequency in June. East Coast Lows will often intensify rapidly overnight making them one of the more dangerous weather systems to affect the NSW coast.

The most recent East Coast Lows to affect NSW were in June 2012. One caused heavy rain up the coast which was coupled with very strong wind gusts of over 100 km/hr. Large waves and coastal erosion were also reported, with maximum wave heights reaching 13.8m at Sydney. The second East Coast Low developed off the north coast on the 10th, with widespread rain between Tweed Heads and Wollongong on the 11th and 12th, heaviest in the Yamba and Sydney regions. This had weaker wind impacts, with a maximum gust of 91 km/hr at Byron Bay on the 12th, and maximum wave heights of 11.3 m at Byron Bay.



Figure 7. Storm brewing over Port Kembla, December 2011. © Dietmar Down Under, Flickr

3 FUTURE CLIMATE PROJECTIONS

This section provides information on Global Climate Models, emissions scenarios and time periods. It also details future projections for atmospheric and ocean variables as well as a final section on extreme weather events.

3.1 Global Climate Models, emissions scenarios and time periods

Global climate models (GCMs) are mathematical representations of the behaviour of the planet’s climate system through time. Each mathematical equation is the basis for complex computer programs used for simulating the atmosphere or oceans of the Earth. In this study, four models were selected by considering the alignment of model results over the regions of Sydney/Port Kembla and also Gladstone, as defined by the CSIRO’s Climate Futures software (Whetton et al. 2012). 18 climate models were sub-divided into pre-defined categories such as “Hotter, Drier” and then assigned a relative likelihood based on the number of climate models that fell within that category. For example, if 9 of 18 models fell into the “Warmer – Drier” category, it was given a relative likelihood of 50% (Clarke et al. 2011). The models selected for Port Kembla were:

- i. **MRI-CGCM2.3.2** - A 'most likely'* future: hotter and little change in rainfall.
- ii. **CSIRO MK3.5** - A 'hot/dry' future: much hotter and much drier.
- iii. **MIROC3.2-Medres** - A 'wetter' future: cooler and wetter.
- iv. **MIROC3.2-Hires** – A 'wetter' future: slightly warmer and wetter.

*Category represented by the greatest number of models.

Modelling future climate change requires an estimation of the concentrations of greenhouse gases and other substances in the atmosphere, in the years to come. **Emissions scenarios** describe these future releases and are the product of complex dynamic systems, determined by factors such as population change, socio-economic development, and technological advances. The two emissions scenarios that were available and selected by the research team were from the ‘A1 storyline’ and were developed by the IPCC Special Report on Emissions Scenarios (SRES). These scenarios are labelled based on their relative greenhouse gas emissions levels, High (SRES A1FI) and Medium (SRES A1B). The team chose not to represent a Low emissions scenario (SRES B1) as much of the literature suggests this scenario may underestimate future emission scenarios (Raupach et al. 2007; Friedlingstein et al. 2010) see Figure 8.

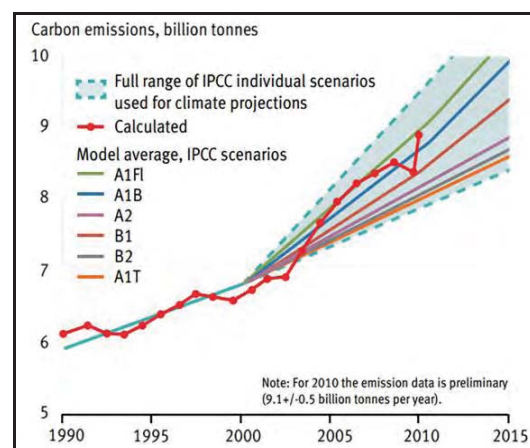


Figure 8. Annual carbon emissions in billion tonnes for 1990-2010. Source:(UNEP 2012).

GCMs project the likely range of changes over decadal to multi-decadal time periods. These **time periods** are expressed relative to the given baseline period and are centred on a given decade. So, the 2050s time period refers to the period 2040-2069. Thirty year time periods provide an average over this range, cancelling out much of the random year-to-year variability. This study focuses on three time periods; the 2030s, 2050s and 2070s.

3.2 Atmospheric projections

The results presented in this section (Tables 2, 3 and 4) show the projected change from the 1975-2004 baseline climate. Data is provided for three time periods and for three models. The 'wetter' model in these projections is based on the MIROC3.2-Medres model. The range shown is from the medium (A1B) to the high (A1FI) emissions scenario.

3.2.1 Temperature

Annual mean temperature projections for Port Kembla (Table 2) show that there is likely to be a slight increase by the 2030s, with a projected increase of 0.7 to 1.2 degrees Celsius (°C) above 1975-2004 values, across the three models. By the 2050s this increases to 1.4 to 2.9°C. Much larger ranges are projected for the 2070s, with increases from 1.7 to 4.0°C above the baseline climate. For Port Kembla, annual mean temperatures may increase from 16.4°C to between 17.8 and 19.3°C in 2050, and to between 18.1 and 20.4°C by 2070. Temperatures of 20°C are equivalent to annual mean temperatures in Brisbane. Despite temperature increases for the 2030s being relatively modest, a small increase in mean temperature can lead to a

large increase in the frequency and severity of extreme heat events. There is also not a large distinction between the emissions scenarios until after the 2030s as temperature patterns do not distinguish from each other until after this period. This is due to the time it takes for each emissions scenario to produce large differences in greenhouse gas concentrations.

3.2.2 Precipitation

Rainfall in coastal regions is difficult to simulate due to changes in weather patterns that cannot be resolved by climate models. This creates a large range of uncertainty for precipitation projections (Table 3). For the 2070s, the 'hotter and drier' model shows decreases of between -10.4 to -14.1%. However, the 'wetter' model projects increases in precipitation of 8.5 to 11.5%. The *NSW Climate Impact Profile* examines seasonal projections and suggests that for the 2050s, the Illawarra region is likely to experience a substantial increase in summer rainfall, a slight to moderate increase for spring and autumn and no significant change for winter.

3.2.3 Relative humidity

Relative humidity projections show decreases for all time periods for the 'most likely' and 'hotter and drier' models (Table 4) which reflect the average projections across Australia. For the 2030s, the 'most likely' model ranges from -0.8 to -0.7% change. By the 2050s, this range increases to -1.4 to -1.8% and by 2070 the reductions are between -1.8 and -2.5% change. The 'hotter and drier' model shows larger reductions for all three time periods, from -2.7 to -2.6% for 2030, -5.0 to -6.3% for 2050 and -6.4 to -8.7% for 2070.

Temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	16.4	0.7	0.7	1.4	1.7	1.7	2.3
'Hotter and drier'	16.4	1.2	1.2	2.3	2.9	2.9	4.0
'Wetter'	16.4	0.7	0.7	1.4	1.7	1.7	2.3

Table 2. Baseline climate and projected annual surface temperature change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Precipitation (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	1094	-0.4	-0.4	-0.7	-0.9	-0.9	-1.3
'Hotter and drier'	1094	-4.4	-4.2	-8.2	-10.2	-10.4	-14.1
'Wetter'	1094	3.6	3.4	6.7	8.3	8.5	11.5

Table 3. Baseline climate and projected annual precipitation change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

Relative Humidity (%)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	74.1	-0.8	-0.7	-1.4	-1.8	-1.8	-2.5
'Hotter and drier'	74.1	-2.7	-2.6	-5.0	-6.3	-6.4	-8.7
'Wetter'	74.1	0.8	0.8	1.5	1.8	1.9	2.5

Table 4. Baseline climate and projected annual relative humidity change for 2030, 2050 and 2070.

Source: Climate Futures, CSIRO.

3.3 Ocean projections

3.3.1 Sea-level rise

Mean sea level rise occurs due to two main processes; the melting of land based ice, which increases the mass of the ocean, and decreases in ocean density, which increases the volume of the ocean. The latter mainly occurs due to increases in the heat content of the oceans which is referred to as thermal expansion.

The IPCC's Fourth Assessment Report (IPCC 2007) projects global mean sea level rise at between 0.21 and 0.59m for the medium and high emissions scenario. Concerns that these projections may have been underestimated (Rahmstorf et al. 2007) have led CSIRO's Centre for Marine and Atmospheric Research (CMAR) to produce updated figures. These projections are based on outputs from the

climate models and include changes in ocean temperature used to estimate changes in sea level due to thermal expansion and estimated flow rates from Greenland and Antarctica (Table 5). The figures show a projected global sea level rise of between 0.22 and 0.81m for the medium and high emission scenario.

As sea levels do not rise uniformly around the globe, regional variations need to be taken into account. Figure 9 shows projections around the Australian coastline. The top panel shows the difference between projected sea level and the global average with the average of all the models shown with the heavy blue line. The bottom panel allows for the identification of regional sea level rise projections at specific locations around the coastline. Each number corresponds with the top panel numbers.

	Medium			High		
	5th percentile	Central estimate	95th percentile	5th percentile	Central estimate	95th percentile
1990	0	0	0	0	0	0
2000	0.01	0.02	0.03	0.01	0.02	0.03
2010	0.02	0.04	0.06	0.02	0.04	0.06
2020	0.04	0.07	0.09	0.04	0.07	0.1
2030	0.06	0.1	0.14	0.06	0.1	0.14
2040	0.08	0.14	0.19	0.08	0.14	0.20
2050	0.1	0.18	0.25	0.1	0.18	0.27
2060	0.12	0.22	0.32	0.13	0.24	0.35
2070	0.15	0.27	0.39	0.16	0.31	0.45
2080	0.17	0.32	0.47	0.19	0.38	0.56
2090	0.19	0.37	0.55	0.23	0.45	0.68
2100	0.22	0.43	0.64	0.27	0.54	0.81

Table 5: Global sea level change (m) over the 21st century, including rapid ice sheet melt, with respect to 1990. The figures shown are for the medium (A1B) and high (A1FI) emissions scenarios, with 5th to 95th percentile confidence intervals. Figures are based on methods outlined in the IPCC's Fourth Assessment Report (Meehl et al. 2007). Source: http://www.cmar.csiro.au/sealevel/sl_proj_21st.html

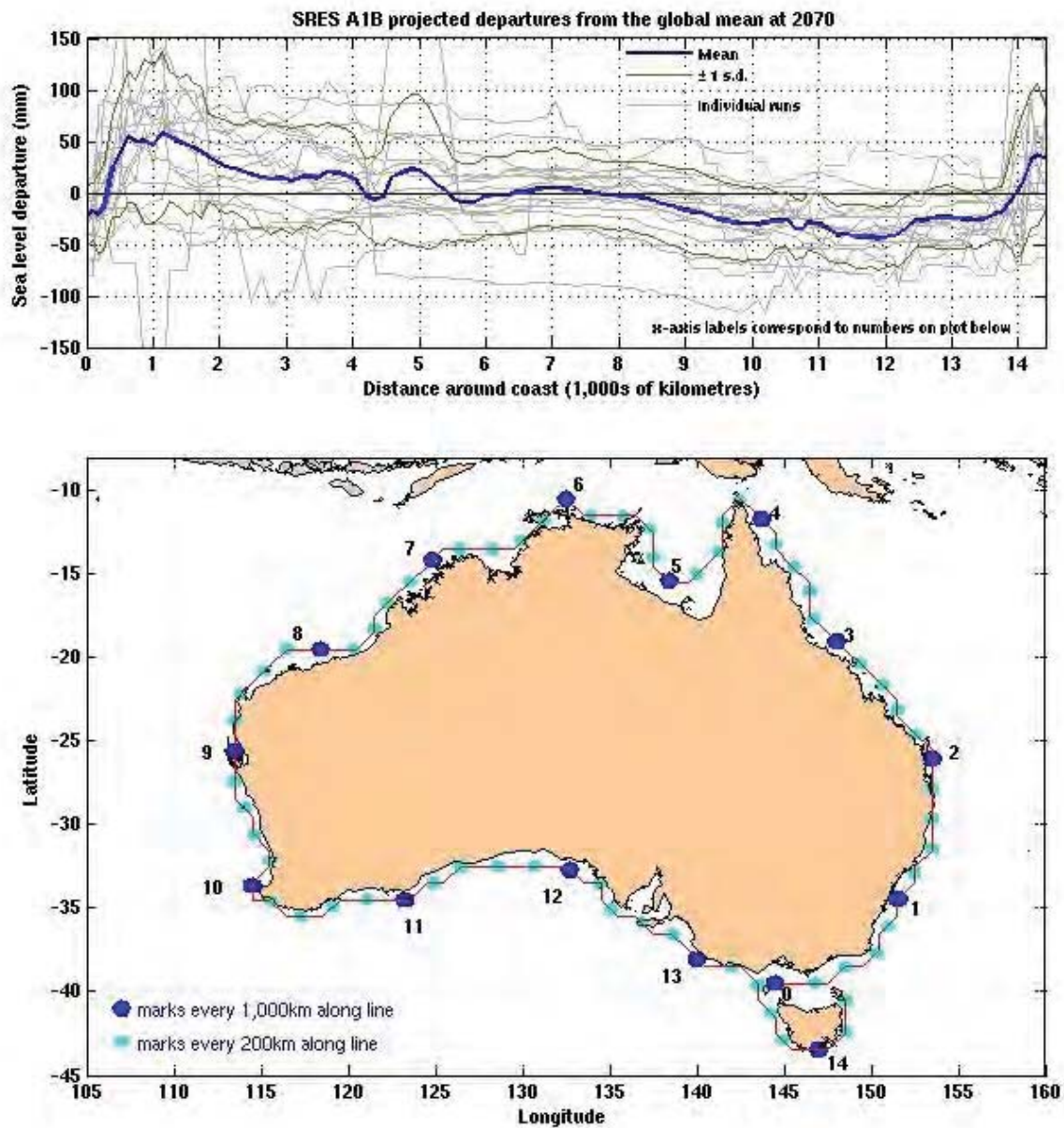


Figure 9: Regional sea level rise projections around the Australian coastline. Figures are derived from the 2070 globally-averaged mean projections for the A1B SRES scenario Source: http://www.cmar.csiro.au/sealevel/sl_proj_regional.html

Table 6 shows projections for global sea level rise together with regional projections taken from 992km around the coast, or just south of point 1 on the map of Figure 9. This point is the location closest to the latitude and longitude of Port Kembla. The sea level

rise projections for Port Kembla in 2030 and 2070 is 16.7 and 49.7cm. It should be noted that sea levels will continue to rise after 2070 and long-term planning should take into account projections after this date.

Component	2030	2070
Sea level rise taken from high emission scenario (Table 5)	0.14m	0.39m
Regional sea level rise variation	0.027m	0.047m
Total	0.167m (16.7cm)	0.437m (43.7cm)

Table 6: Components of sea level rise including CSIRO's updated CMAR figures together with regional projections derived from the global average (see Figure 9).

Sea-level rise will create a significant risk to properties, infrastructure and beaches along the coastal areas of NSW (Steffen & Hughes 2012). The main threats from sea-level rise will be:

1. Storm-related flooding
2. Flooding from higher sea levels
3. Erosion of the land

1. Storm surge flooding

During severe storm events the impacts of sea-level rise are more apparent. When a storm event coincides with a storm surge and high tide, small rises in sea level can result in very large increases in the frequency of coastal flooding (ACE CRC 2008; J. Church et al. 2006). Around Sydney, flooding that is currently considered a 1-in-100 year event could occur every few months with a sea-level rise of 0.5m (Figure 10).

2. More regular flooding

With a 1.1m rise in sea level in NSW:

- Parts of Sydney airport, the busiest in Australia, would be flooded with a storm surge, interrupting operations and damaging infrastructure
- Over 170km of railway would be at risk, with a replacement value of up to \$1.3

billion. Wollongong and Newcastle have the longest lengths of railway of NSW cities at risk from a 1.1m sea-level rise – 43–51 km and 49–56 km respectively (DCCEE 2011).

3. Erosion

Higher sea levels can cause erosion of beaches, and the retreat of soft coastlines further inland. Coastal erosion can undermine buildings and infrastructure, such as roads and railways. Approximately 3,600 residential buildings in NSW are located within 110 metres of soft shorelines (Steffen & Hughes 2012).

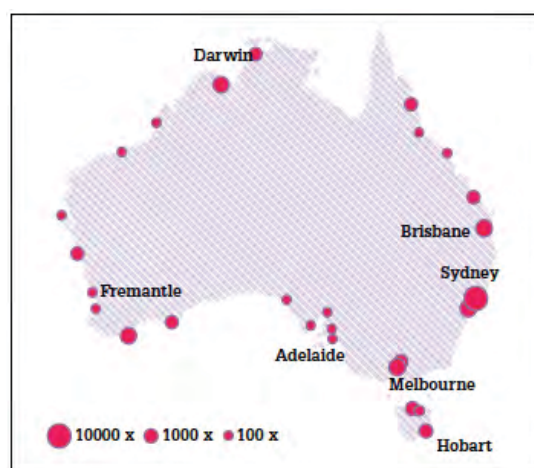


Figure 10. Estimated increase in the frequency of high sea-level events caused by a sea-level rise of 0.5m. Source ACE CRC 2008.

3.3.2 Ocean temperature and salinity

This section considers the temperature of the sea surface (or sea-surface temperature - SST) and sea-surface salinity (SSS). As before, projections are derived for three 30-year time periods centred on 2030, 2050 and 2070, relative to the 1975 to 2004 baseline. The research team aimed to keep all of the variables consistent, however, the MIROC3.2 Medres model was not available for sea surface temperature and only 'wetter' models were available for salinity. The MIROC3.2-Hires model therefore replaces the MIROC3.2 Medres model in the sea

surface temperature results and is the only model used in the salinity results.

Sea-surface temperatures for the Port Kembla region are projected to increase by 0.6 to 1.0°C for the 2030s, 1.1 to 2.1°C for the 2050s and 1.5 to 3.4°C for the 2070s.

Sea-surface salinity (SSS) is the measure of the concentration of dissolved salt in the sea water, at, or very close to the ocean surface. Sea-surface salinity projections show no significant change with an increase in practical salinity units (psu) from 35.5 to between 35.6 to 35.7 from 2030 to 2070.

Sea surface temperature (°C)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Most likely'	19.3	0.6	0.6	1.1	1.2	1.5	2.0
'Hotter and drier'	19.3	0.9	0.9	1.6	1.9	2.2	1.9
'Wetter'	19.3	1.1	1.0	1.8	2.1	2.5	3.4

Table 7. Baseline climate and projected annual sea surface temperature change (°C) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

Sea surface salinity (psu)

Model	Baseline 1975 -2004	2030		2050		2070	
		A1B	A1FI	A1B	A1FI	A1B	A1FI
'Wetter'	35.5	0.1	0.1	0.1	0.1	0.1	0.2

Table 8. Baseline climate and projected annual sea surface salinity change (PSU) for 2030, 2050 and 2070. Source: OzClim, CSIRO.

3.4 Extreme weather events

Data from CSIRO is not as comprehensive for extreme weather events as the more common variables. The medium emissions scenario (A1B) was not available for the 2050s and 2070s so the low emissions scenario (B1) has been used to present a projected range. The 'most likely' model also did not provide projections for hot days and very hot days. These projections have been derived for the Sydney/Port Kembla region and the results presented here are the best available to date.

3.4.1 Hot days and very hot days

The total number of hot days, defined by the World Meteorological Organisation as "Annual count of days with maximum temperature > 35°C", is expected to increase from 3.5 to between 5.2 and 5.8 days by the 2030s. By the 2050s this increases to between 8.3 to 15.3 days, under a high emissions scenario. Much larger increases are projected for the 2070s with a range of 11.2 to 26 days. For hot days during the summer months, defined here as December, January and February, the range is between 8.2 to 16.5 days. Therefore two thirds of these hot days are projected for these 3 months of the year. These projections will have significant consequences for operations that need to cease when temperatures exceed 35°C or indeed for workers that require more breaks.

The number of days where maximum temperatures are greater than 40°C is far less, both annually and for the summer months. Currently the number of days exceeding this temperature is 0.3 and 0.2 days respectively. By the 2050s this could reach between 0.9 and 2.0 days per year and for the 2070s, between 1.4 and 4.3 days per year.

3.4.2 Extreme precipitation

Overall, climate change projections for NSW highlight increases in the occurrence of extreme rainfall events for many parts of the state. These events are most likely to occur in summer and autumn months, with the most vulnerable regions being eastern coastal regions, and central and south-east NSW (CSIRO 2004).

3.4.3 Extreme wind speed

Extremes in wind contribute directly to hazardous conditions causing damage to the built and natural environment. They also create hazardous conditions over oceans and are responsible for the generation of storm surges and large waves which can cause coastal inundation and increase coastal erosion. Even modest changes in wind speed can alter the wave climate.

Annual days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	3.5	5.8	-	6.3	15.3	8.5	26.0
'Wetter'	3.5	5.2	-	5.3	8.3	6.2	11.2

Table 9. Baseline climate and projected days per annum over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Annual days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	0.3	0.6	-	0.7	2.0	0.9	4.3
'Wetter'	0.3	0.5	-	0.5	0.9	0.6	1.4

Table 10. Baseline climate and projected days per annum over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 35°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	2.8	4.1	-	4.5	10.1	5.7	16.5
'Wetter'	2.8	4.0	-	4.1	6.2	4.7	8.2

Table 11. Baseline climate and projected summer days over 35 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

Summer days over 40°C

Model	Baseline (1975 -2004)	2030		2050		2070	
	Days	A1B		B1	A1FI	B1	A1FI
'Hotter and drier'	0.2	0.5	-	0.5	1.4	0.7	3.1
'Wetter'	0.2	0.4	-	0.4	0.7	0.5	1.1

Table 12. Baseline climate and projected summer days over 40 degrees Celsius for 2030, 2050 and 2070. Source: CSIRO.

4 BIBLIOGRAPHY

ACE CRC, 2008. *Briefing: A Post-IPCC AR4 Update on Sea-level Rise*, Hobart, Tasmania. Available at: http://www.cmar.csiro.au/sealevel/downloads/797655_16br01_slr_080911.pdf

Australian Bureau of Statistics, 2001. How many people live in Australia's coastal areas? Available at: [http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0FeatureArticle32004?opendocument&tabname=Summary&prodno=1301.0&issue=2004&num=&view=.](http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0FeatureArticle32004?opendocument&tabname=Summary&prodno=1301.0&issue=2004&num=&view=)

CSIRO, 2004. Climate Change to Increase extreme Rainfall.

CSIRO & Bureau of Meteorology, 2012. *State of the Climate*, Available at: <http://www.csiro.au/en/Outcomes/Climate/Understanding/State-of-the-Climate-2012.aspx>.

Church, J. et al., 2006. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine*, 55, pp.253–260.

Clarke, J., Whetton, P. & Hennessy, K., 2011. Providing application-specific climate projections datasets: CSIRO's Climate Futures Framework.

DCCEE, 2011. *Climate Change Risks to Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment*, Commonwealth of Australia, Canberra.

Department of Environment Climate Change and Water, 2010. *NSW Climate Impact Profile*, Available at: <http://www.environment.nsw.gov.au/climateChange/20100171ClmtChngNSW.htm>.

Department of Planning and Infrastructure, 2012. *Illawarra Urban Development Program*, Available at: <http://www.planning.nsw.gov.au/LinkClick.aspx?fileticket=d1lK5wfqLhs=&tabid=196&language=en-US>.

Friedlingstein, P. et al., 2010. Update on CO2 emissions. *Nature Geoscience*.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. In S. Solomon et al., eds. Cambridge, United Kingdom and New York, NY, USA.

Office of Environment and Heritage, 2011. *NSW Climate*. Available at: <http://www.environment.nsw.gov.au/bioregions/BioregionsNswoutlineClimate.htm>

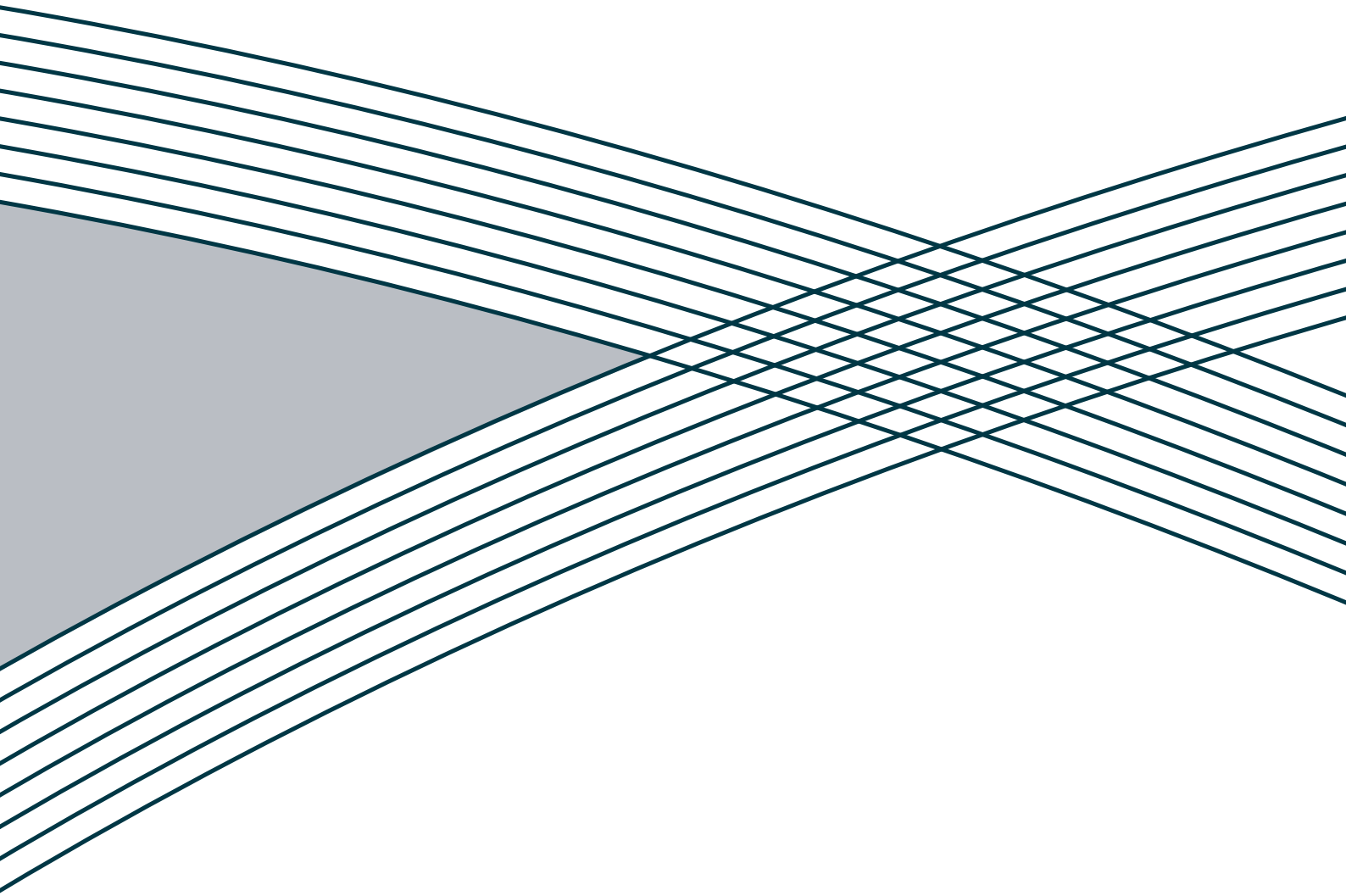
Rahmstorf, S. et al., 2007. Recent Climate Observations Compared to Projections. *Science*. Available at: http://www.pik-potsdam.de/~stefan/Publications/Nature/rahmstorf_etal_science_2007.pdf

Raupach, M.R. et al., 2007. Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 104(24), pp.10288–93. Available at: <http://www.pnas.org/cgi/content/long/104/24/10288>

Steffen, W. & Hughes, L., 2012. *The Critical Decade: New South Wales climate impacts and opportunities*,

UNEP, 2012. *GEO5: Summary for Policy Makers*, Available at: http://www.stakeholderforum.org/fileadmin/files/GEO5_SPM_English.pdf [Accessed October 25, 2012].

Whetton, P. et al., 2012. Use of Representative Climate Futures in impact and adaptation assessment. *Climatic Change*, pp.1–10.



NCCARF
National
Climate Change Adaptation
Research Facility



RMIT
UNIVERSITY