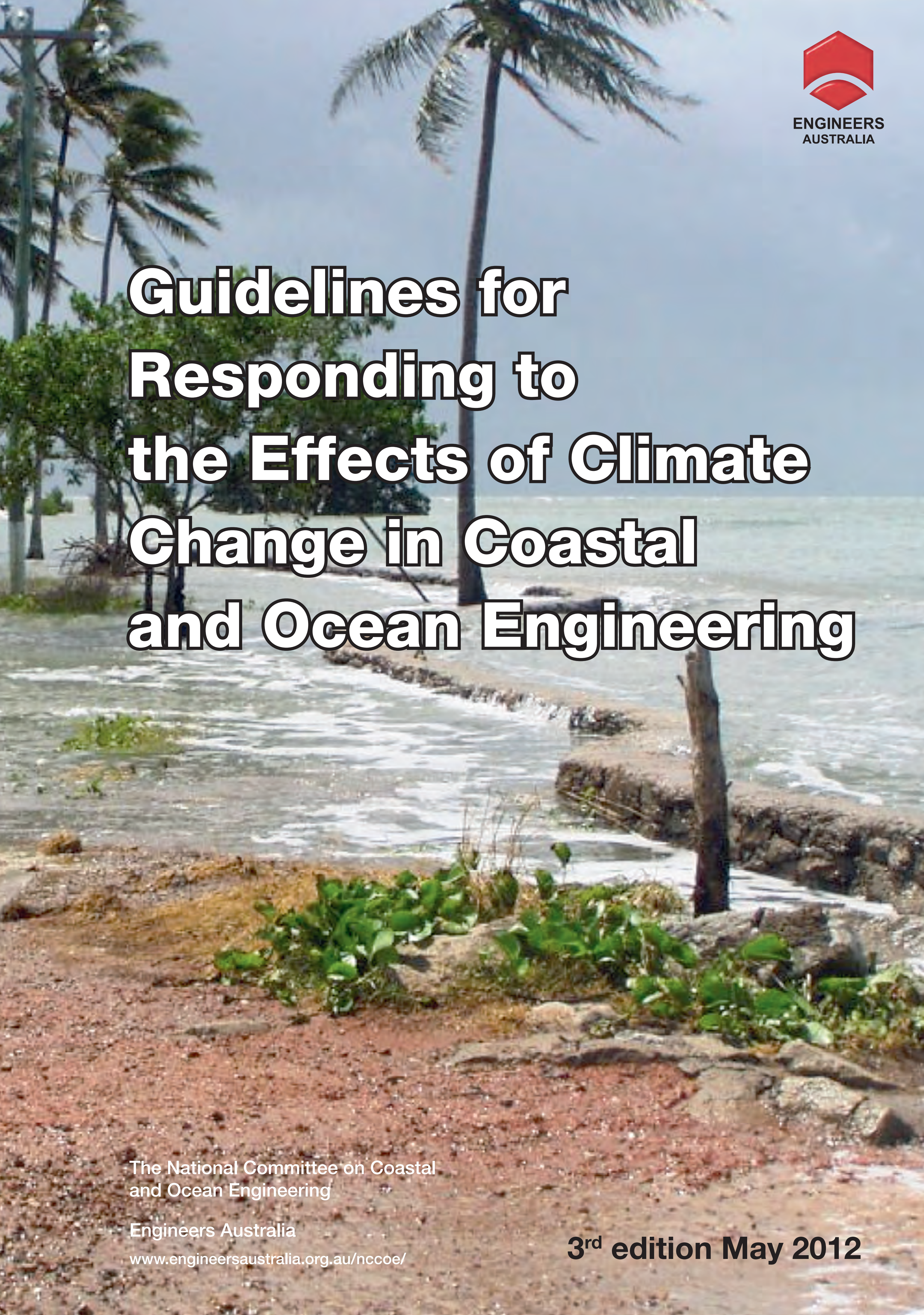

ENGINEERS
AUSTRALIA

Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering

The National Committee on Coastal
and Ocean Engineering

Engineers Australia

www.engineersaustralia.org.au/nccoe/

3rd edition May 2012

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This document is prepared by the National Committee on Coastal and Ocean Engineering, Engineers Australia, for the guidance of coastal engineers and other professionals working with the coast who should accept responsibility for the application of this material.

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2nd edition: updated by Bruce A Harper (Systems Engineering Australia).
3rd edition: updated by Bruce A Harper (Systems Engineering Australia), edited by Doug Lord & Murray Townsend (NCCOE).

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This publication has been subject to a peer review process.

National Library of Australia Cataloguing-in-Publication entry

Harper, Bruce A.

Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering / Engineers Australia National Committee on Coastal and Ocean Engineering.

3rd ed.

ISBN: 9780858259195 (pbk.)
9780858259270 (ebook: pdf)

Includes bibliographical references.

Climatic changes – Australia.
Coastal engineering – Environmental aspects – Australia.
Coastal zone management – Australia

551.60994

NCCOE Guidelines Series

1. Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering, 3rd ed, 2012. (this document).
2. Coastal Engineering Guidelines for working with the Australian coast in an ecologically sustainable way, 2nd ed, 2012.
3. Climate Change Adaptation Guidelines in Coastal Management and Planning.

Published by Engineers Media and distributed by EA Books, PO Box 588, Crows Nest NSW 1585, Australia
Phone: 02 9438 5355 Fax: 02 8823 6526
www.eabooks.com.au

Cover photo: Saibai Island, Torres Strait, Jan 2009 during Tropical Cyclone Charlotte.
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Figure 1 reproduced from the *Bulletin of the American Meteorological Society*.

PREFACE

These guidelines have been prepared by the National Committee on Coastal and Ocean Engineering (NCCOE) of Engineers Australia (EA) and represent an update and extension of the 2004 guidelines, based on a methodology first developed in 1991, which is outlined in **Appendix A** for reference. The NCCOE was formed in 1971 and is an honorary group of specialist engineering professionals, whose objective is to advance the science and art of coastal and ocean engineering throughout the general engineering profession and the community, by such means as:

- facilitating initial and continuing education in our field
- assisting in relevant tertiary course accreditation
- encouraging and setting priorities for research
- ensuring the availability of technical standards
- encouraging good coastal and ocean engineering practice
- providing a forum and a network for the exchange of views and experience
- formulating policy for Engineers Australia in the coastal and ocean area
- fostering interaction between the profession and the public on technical and social issues.

Funding for the preparation of these guidelines was mainly provided by income received from the biennial NCCOE-sponsored Australasian Coastal and Ocean Engineering Conference series. The NCCOE acknowledges funding assistance from the Commonwealth Department of Climate Change and Energy Efficiency in finalisation and publication of this edition.

This document is provided for the guidance of coastal and ocean engineers, who are expected to accept responsibility for their interpretation and application of the material provided. In particular, users should be aware that adoption of the recommended allowances, strategies and approaches in this document may not in itself be sufficient to gain development approval under Commonwealth, State or Local Government policies, where specific legislation, regulations, policy and guidelines might exist.

DEDICATION

This publication is dedicated to the memory of the late Dr David Wilkinson, former NCCOE member and distinguished academic in the field of coastal and ocean engineering. David, who unexpectedly passed away in 1998, was a principal contributor to the first edition of this document completed in 1991 and was a co-recipient of the NCCOE Kevin Stark Memorial Award for excellence in coastal and ocean engineering in 1997.

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1. INTRODUCTION

1.1 Background

This document updates previous climate change guidelines prepared by the National Committee on Coastal and Ocean Engineering (NCCOE, 1991; refer also **Appendix A** herein, and NCCOE, 2004a), and is designed to complement the coastal engineering guidelines for ecologically sustainable development (NCCOE, 2004b) which are currently being upgraded. It represents an expansion of the earlier documents made in response to requests from the coastal and ocean engineering profession in Australia and fulfils a need to reflect the most recent climate change scenarios. Climate science itself continues to evolve at a rapid rate and it is expected that further updated NCCOE climate change guidelines will be prepared in future.

Over the past two decades there has been a growing awareness of the potential impacts that human-induced global climate change may have, and especially its possible effects on the coastal and ocean environment. This awareness has been raised to the extent that many approving bodies now insist that climate change effects be taken into account in all new development applications. This document has been prepared to provide the coastal and ocean engineering professional with guidelines for implementing coastal zone management strategies and for facing the many engineering issues raised by the possibility of a changing global climate.

It is therefore essential that the professional coastal and ocean engineer continues to exercise good judgement in response to the possible impacts of climage change.

In the past (prior to the 1991 Guidelines), engineers relied on the assumption that the natural environment, although highly variable, remains statistically static and that probability distributions for prime environmental factors such as wind speed, wave height, flood frequency and sea level are unchanging with time. Efforts have therefore centred on the already difficult problem of estimating the underlying natural statistical variability of these phenomena through long term measurement programs, sophisticated numerical modelling and statistical simulation. The proven rise in carbon dioxide levels and the possibility of the Earth being subject to a changing climate over engineering timescales has brought some aspects of this basis of design into question. Extrapolation of probability distributions to exposure times very much longer than the data base may be invalid in a changing environment unless some specific account can be taken of those changes. The NCCOE believes that the weight of scientific opinion suggests that changes to climate may occur within the design life of many coastal and ocean engineering activities. Consequently, consideration of the possible impacts of climate change should be included in the design process.

The potential impacts of climate change must be considered along with existing natural variability. The timescale of the asset /project under consideration will determine the relative importance of the climate change impacts. Natural climate variability on a regional basis (setting aside human-induced climate change) remains the single greatest source of uncertainty affecting engineering assessments of risk and in providing appropriate societal solutions by way of strategies, interventions or structures. For example, there is presently no substantiated increasing trend in the global occurrence of severe weather related events that can be locally quantified for design purposes. However, the increasing population in the coastal zone has itself significantly increased the exposure of the modern coastal society to extreme coastal events. Also, the quasi-steady ENSO (El Niño – Southern Oscillation) phenomenon, which has been the subject of intensive research and data gathering for many years, provides multi-seasonal variability that is of similar magnitude to some projected aspects of long term climate change. Our overall responses to climate change should therefore be seen as an expansion of our current methodologies, which are integral to the sustainable development and management of the coastal and ocean zone, and where natural variability and more direct and quantifiable human effects still presently dominate.

The problem of possible global climate change in a relatively short time frame highlights the lack of knowledge about many essential aspects of our complex ecosystem, raises many questions and demands hypotheses about the possible response of systems for which we do not yet have a full understanding. Accordingly, some of the popular debate remains somewhat pessimistic, with the tendency to emphasise the possible extremes rather than the more probable outcomes. The literature is diverse and extensive and can be repetitive, making casual enquiries difficult.

In spite of the enormous and growing body of scientific literature and knowledge of climate change, there are unlikely ever to be accurate predictions of its effects (in both time and magnitude) or panaceas for the possible impacts. It is therefore essential that the professional coastal and ocean engineer continues to exercise good judgement in response to the possible impacts of climate change. The engineering profession must continue to work with the broader climate science community to improve and integrate our understanding of future climate variability.

1.2 Content and Use

This update sets out to summarise the causes of atmospheric warming due to the enhanced greenhouse effect and identifies the primary climate-sensitive factors for various types of coastal engineering activities. Guidelines are then provided that should assist an experienced coastal and ocean engineer to assess the significance of climate change for a particular situation or project using a risk-based approach. The format of this update follows the 2004 version and the overall methodology and recommended assessment process remains essentially unchanged. This update also has the benefit of some updated knowledge that has become available post-IPCC (2007).

The document provides:

- an introduction to climate change
- latest global scenario projections
- guidelines for response and adaptation measures
- resources for further enquiry
- a recommended methodology for engineering impact assessment
- example assessments.

The document is designed primarily for use by professional engineers, whose experience and qualifications meet or exceed those presented in Appendix B, with expertise in and responsibility for works and facilities within the coastal and ocean field. Recognised areas of speciality and experience may include:

- ports and harbours, dredging and reclamation
- breakwaters, seawalls and revetments
- sediment transport, beach nourishment
- coastal management and planning
- coral reefs and islands
- hydraulics of estuaries, rivers and canals
- water quality, mixing and dispersion
- physical hydraulic scale modelling
- numerical modelling of tides, currents, waves and storm surge
- data collection and analysis
- natural hazards risk assessment
- vessel motion analysis
- marine pipelines and offshore structures
- design criteria assessment
- meteorology and oceanography
- statistics of extremes.

It is emphasised that this document provides guidelines only and it remains the responsibility of the user to apply appropriate professional judgement to each application.

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2. CLIMATE CHANGE

2.1 The Intergovernmental Panel on Climate Change

The primary consensus reference on climate change is the Intergovernmental Panel on Climate Change (IPCC). The IPCC was jointly established by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) in 1988. Its role is:

> *"… to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation."*

The IPCC's First Assessment Report was completed in August 1990 and served as the technical basis for the United Nations Framework Convention on Climate Change in 1992 (UNFCCC). Its objective is the:

Most systems are sensitive to climate change. Natural ecological systems, socioeconomic systems and human health are all sensitive to both the magnitude and rate of climate change. (IPCC, 1996b)

> *"… stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."*

Since 1992, the Kyoto protocol (1997), Bali Roadmap (2007), Cancun Agreements (2010) and Durban Platform for Enhanced Action (2011) have all reinforced the need to curb greenhouse gas emissions.

The greatest single contribution to global warming is deemed to be due to increases in atmospheric CO_2 since the commencement of the industrial revolution, *circa* 1750. The inaugural NCCOE guidelines document (NCCOE 1991) reported the IPCC 1990 findings and NCCOE (2004a) reflected the IPCC (2001) Third Assessment Report (TAR). The present document reflects the revised and updated IPCC (2007) position from Assessment Report Four (AR4).

The Australian Government interpretation of the IPCC projections and impacts is provided in a number of technical and non-technical reports, through the Department of Climate Change and Energy Efficiency, available on-line at http://www.climatechange.gov.au.

Many of the following extracts and summaries are derived directly from IPCC (2007) unless otherwise indicated. The discussion here is targeted towards issues that are specifically relevant to coastal and ocean engineering activities. The complete IPCC documents should be consulted by those requiring a more expansive and inclusive treatment of the subject and downloadable versions of the technical reports and summaries are freely available from http://www.ipcc.ch. IPCC figures here are reproduced with permission.

2.2 The Scientific Basis of Climate Change

2.2.1 The Global Warming Process

This topic is addressed by Working Group I of the IPCC (IPCC, 2007b), which reports considerable progress having been made in the understanding of climate change since 2001 with new data and more accurate analyses becoming available.

The earth absorbs radiation from the Sun, mainly at the surface. This energy is then redistributed by the atmospheric and oceanic circulation, and radiated to space at longer ("terrestrial" or infrared) wavelengths. On average, for the Earth as a whole, the incoming solar radiation is balanced by the outgoing terrestrial radiation. Any factor that alters the radiation received from the Sun or lost to space, or which alters the redistribution of energy within the atmosphere, and between the atmosphere, land and ocean, can affect climate. A change in the energy available to the Earth/atmosphere system is termed a *radiative forcing*.

Figure 1 summarises the Earth's estimated energy balance as recently updated by Trenberth et al. (2009) using the latest satellite and other observational datasets and numerical models[1]. Some of the infrared radiation leaving the atmosphere originates near the Earth's surface and is transmitted relatively unimpeded through the atmosphere. The bulk of the radiation, however, is intercepted and absorbed by the atmosphere that in turn emits radiation both up and down. Most of the atmosphere consists of nitrogen and oxygen (99% of dry air) that are transparent to infrared radiation. However, water vapour (0 to 2%), carbon dioxide, methane, ozone and some other minor gases absorb some of the surface thermal radiation. These *radiatively* active gases are also termed greenhouse gases because they act as a partial blanket increasing the surface temperature of the Earth above what it would otherwise be, analogous to the effects of a greenhouse. Furthermore, as the climate system warms, the atmosphere is able to hold more water vapour, which in turn increases warming; a positive feedback effect. Water, as clouds, is radiatively active but also reflects solar radiation. The overall balance of contributions remains a subject of research. The natural presence of greenhouse gases

Without natural heat-trapping greenhouse gases the Earth's surface would have an average temperature of -18°C rather than our current average of 15°.

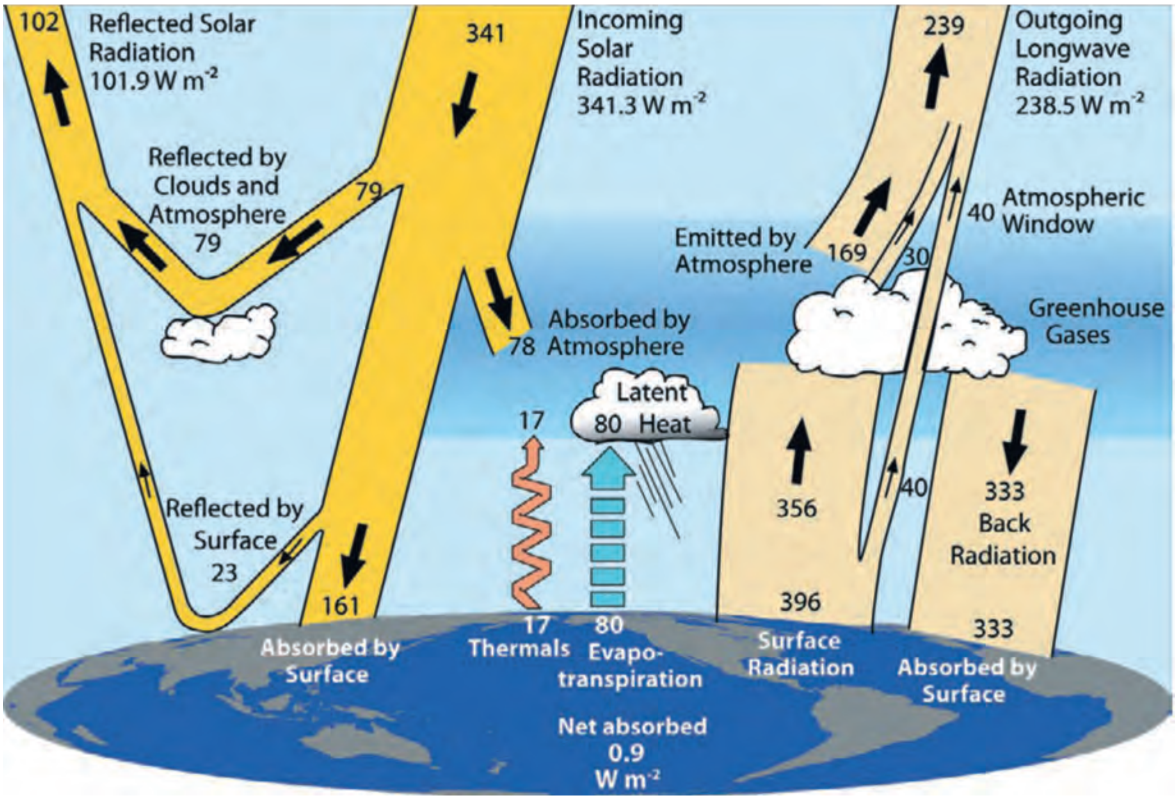

Figure 1: The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period ($W\ m^{-2}$). The broad arrows indicate the schematic flow of energy in proportion to their magnitude (after Trenberth et al., 2009, fig 1).

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[1] This update has significant changes in some energy components compared with IPCC (2007) reflecting the degree of uncertainty and rates of progress still in the science at this time.

has been a positive and necessary feature of the development of life on Earth. Without heat-trapping greenhouse gases the surface would have an average temperature of -18 °C rather than our current average of 15 °C.

The climate can vary for many reasons. Human activities, in particular, can lead to changes in atmospheric composition and hence radiative forcing through, for example, the burning of fossil fuels, wide scale deforestation or through processes that increase the number and distribution of man-made aerosols (very small airborne particles and droplets). Large scale changes in land uses that alter properties of the Earth's surface can also give rise to changes in local climate (for example, construction of cities or clearing of rainforests). Synthetic aerosol gases such as CFCs and HCFCs are also radiatively active, but because they act to deplete stratospheric ozone levels, their net radiative forcing effect is relatively low.

The additional surface heating component of human-induced (or anthropogenic) origins is referred to as the *enhanced greenhouse* effect. Because of the relative radiative forcing potential of each of the primary gases, the principal contributing man-made effect is from CO_2, the excess amounts of which can be expected to remain in the atmosphere for many decades to centuries. If CO_2 emissions were maintained at 1994 levels, it was estimated (IPCC, 1996a) that this would lead to a nearly constant rate of increase in atmospheric CO_2 concentrations for at least two centuries, reaching about 500 ppm (approaching twice the pre-industrial concentration of 280 ppm) by the end of the 21st century. This prediction was the basis of the commonly referred to "$2 \times CO_2$" scenario of an enhanced greenhouse world.

The IPCC AR4 (2007) estimated that the change in global mean near-surface air temperature that would result from a sustained doubling of the atmospheric CO_2 concentration would likely be in the range 2 °C to 4.5 °C with a best estimate of about 3 °C.

A warming atmosphere ultimately implies a warming ocean that, through a variety of processes, is expected to cause an increase in mean sea level. Coupled with this is the possibility that large-scale weather patterns and extreme events may also be altered as a result of the warming of the Earth.

Most of the observed increase in global average temperatures over the past 50 years is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007a).

2.2.2 Evidence of Climate Change

By 1995 the balance of evidence had already suggested that there had been a discernible human influence on global climate since the late 19th century (IPCC, 1996a). In addition, in the light of new evidence and taking into account the remaining uncertainties, most of the observed increase in global average temperatures over the past 50 years is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007a).

This conclusion is supported by the following observations (IPCC, 2007b):

- The 1990s are likely to have been the warmest decade of the millennium (since 1860) and 1998 and 2005 were the warmest two years in the instrumental global surface air temperature record. More recently the World Meteorological organisation (WMO) announced that globally 2010 ranked as the warmest year on record (together with 1998 and 2005), with 2001-10 now being the warmest decade on record[2].
- Global mean surface air temperature has increased by 0.74 °C (95% confidence of ±0.18 °C) over the past 100 years (Figure 2).
- Regional changes in precipitation have been increasingly observed.

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[2] http://www.wmo.int/pages/publications/showcase/documents/1074_en.pdf

- By 2005, the atmospheric concentrations of important long-lived greenhouse gases, *inter alia* carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), had grown significantly: by about 35%, 150% and 18% respectively since pre-industrial times, i.e. since about 1750 (Figure 3).
- The rate of globally-averaged sea level rise measured by tide gauges from 1961 to 2003 is 1.8 ±0.5 mm/y (Figure 4). Local variations from this global average occur at individual gauges. The global average rate of sea level rise measured by TOPEX/Poseidon satellite altimetry during the recent decade 1993 to 2009 is 3.2 ±0.4 mm/y. These measurements are tracking closely to the projected upper limits of anthropogenic warming modelling (e.g. Church & White, 2011).

With respect to regional sea levels, the Bureau of Meteorology National Tidal Centre (previously the Australian National Tidal Facility at Flinders University) has been collecting, archiving and disseminating sea level and related material for over 30 years, and an extract of data from some long-term Australian tidal stations is presented in Figure 5 (BoM, 2007). The longest reliable record is from Fremantle in Western Australia spanning over 100 years, followed by Fort Denison in Sydney Harbour with over 90 years. The mean sea level trend in mm/y is indicated against each record. Taking all 35 sites in Australia where the record is at least 25 years long, the average trend in sea level is +0.8 mm/y (1.3 mm standard deviation). A censored sample from 27 stations where trends are within one standard deviation of the mean indicates a trend of 1.2 mm/y (0.5 mm). Of particular significance for many of these records is the high variability on a decadal timescale, with many stations recording lowering sea levels in the past decades, likely attributable to the relatively persistent El Niño condition during that time, a measure of which is indicated on the figure by depression of the Southern Oscillation Index (SOI).

Since the early 1990s, the National Tidal Centre of the Bureau of Meteorology (formerly the National Tidal Facility of Flinders University) has been undertaking the Australian Baseline Sea Level Monitoring Project. Data are collected from an array of 14 standard sea level monitoring stations at representative sites around the Australian coastline. Yearly data reports are available on-line at:

http://www.bom.gov.au/oceanography/projects/abslmp/reports_yearly.shtml.

The Annual Sea Level Data Summary Report: July 2010–June 2011 shows wide variations in net relative sea level rises, from 2.6mm/y at Port Kembla since July 1991 to 9 mm/y at Hillarys since November 1991. However, the report states that: "The sea level records for all stations, when corrected

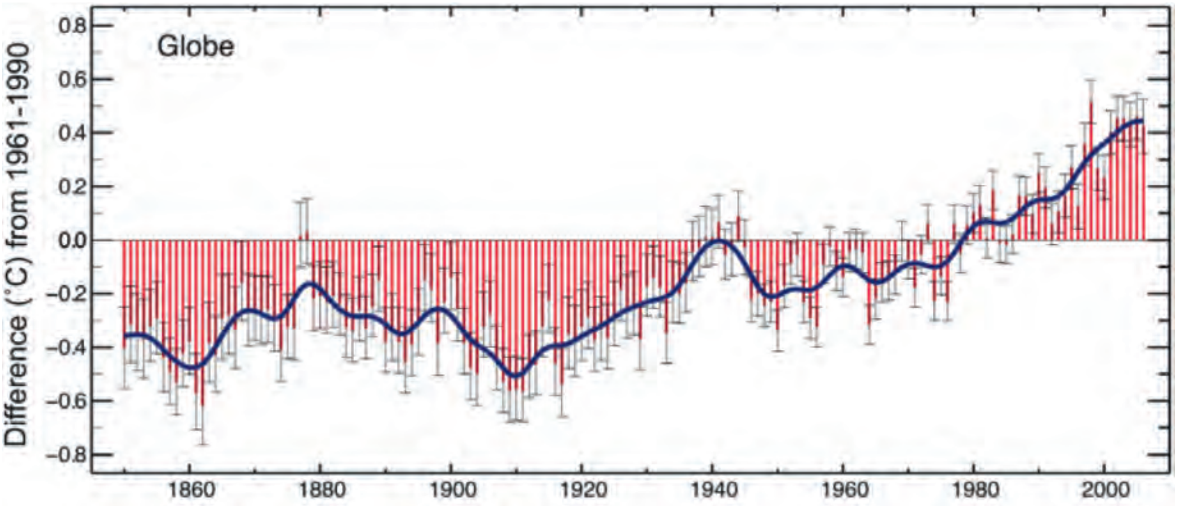

Figure 2: Global annual combined land-surface air temperature and SST anomalies (°C) (red) for 1850 to 2006 relative to the 1961 to 1990 mean, along with 5% to 95% error bar ranges, from HadCRUT3. The smooth blue curves show decadal variations (after IPCC 2007b, fig 3.6 extract).

The projected range of mean increase in global surface air temperature by the year 2095 is 1.8 °C to 4 °C. (IPCC, 2007a)

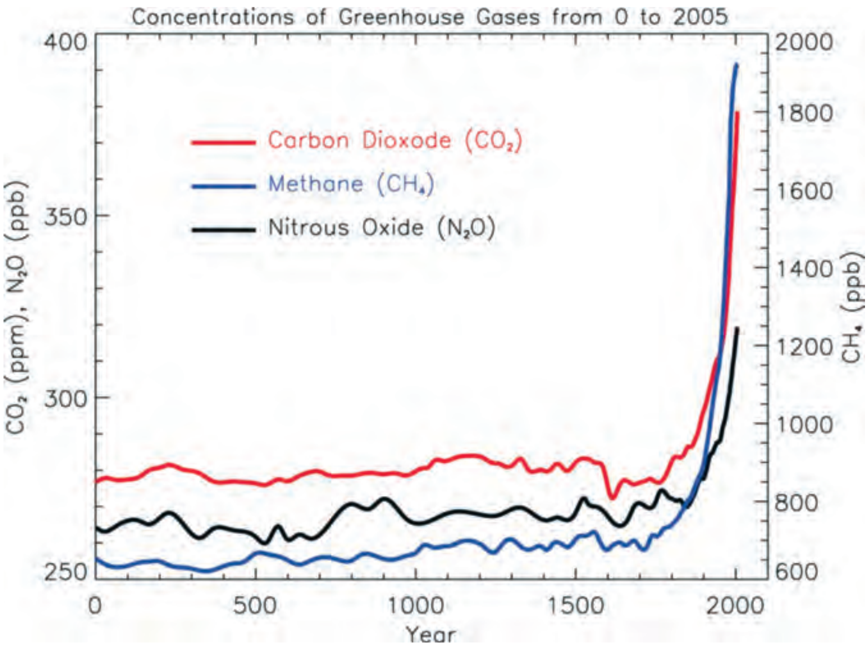

Figure 3: Fluctuating greenhouse gas concentrations in the atmosphere (after IPCC, 2007a, FAQ 2.1, fig 1).

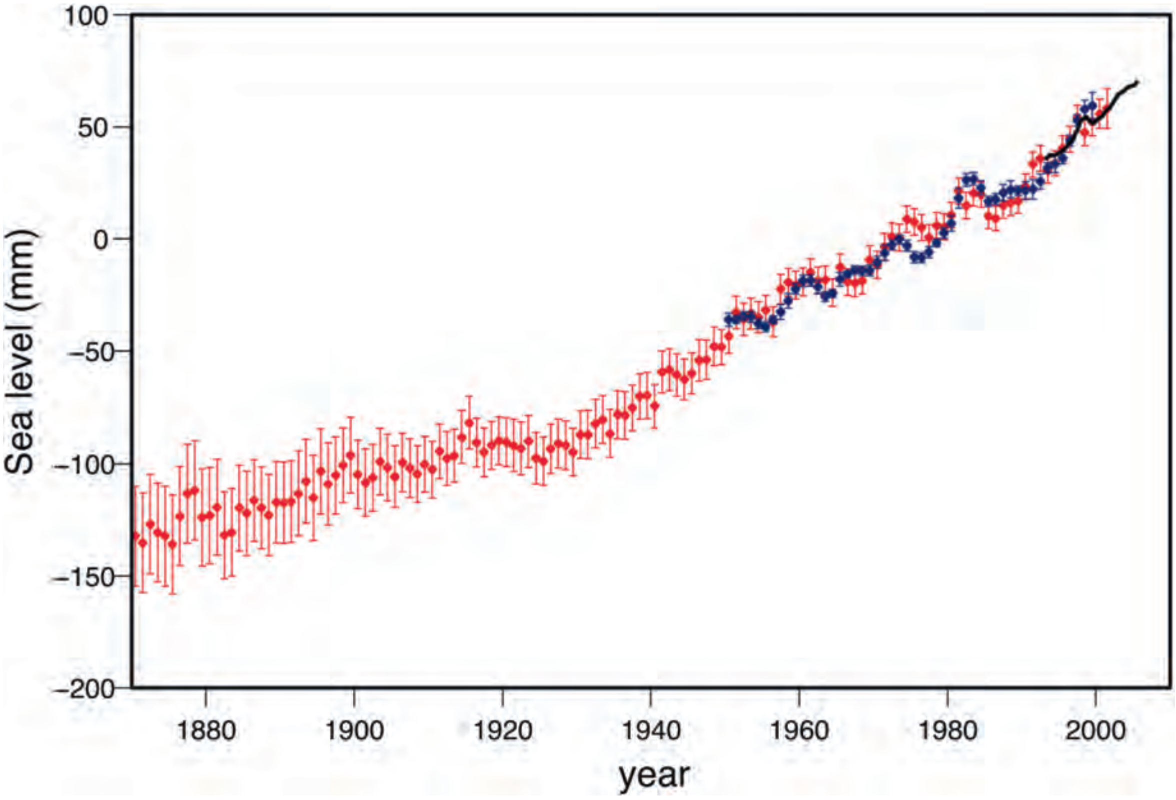

Figure 4: Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870; the blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry. Error bars show 90% confidence intervals (after IPCC, 2007b, fig 5.13).

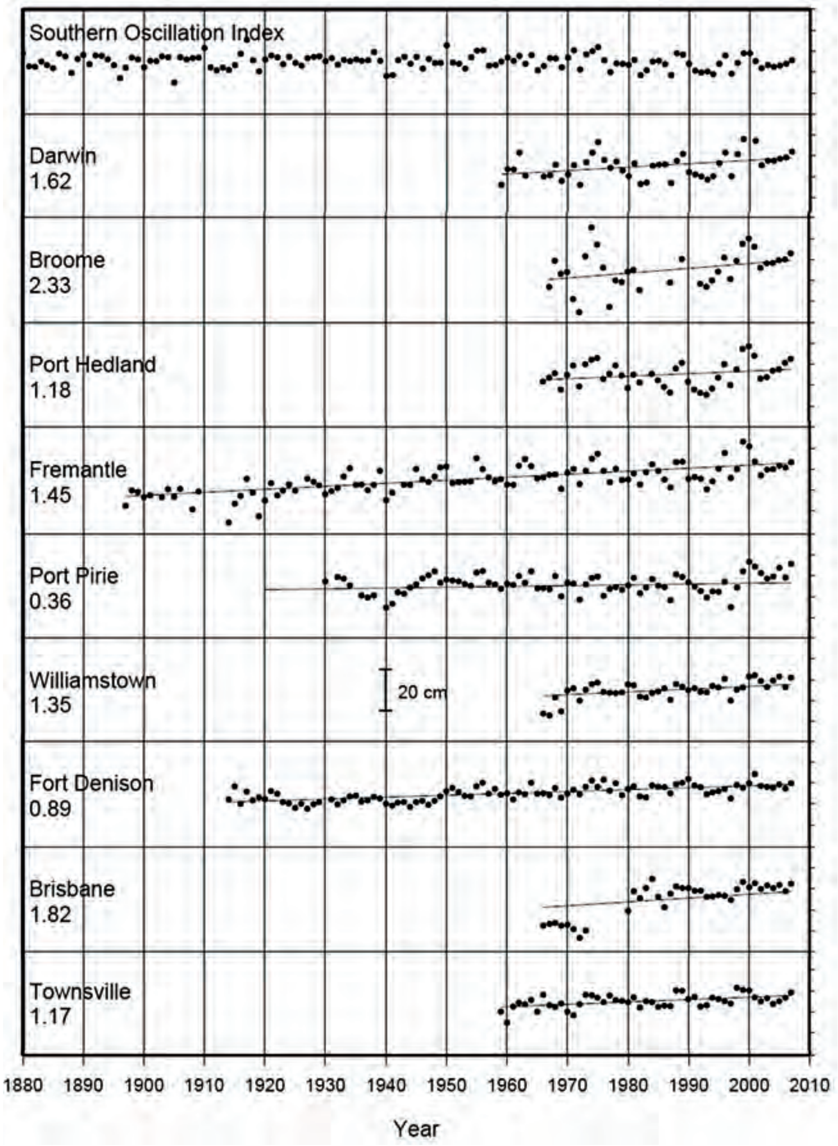

Figure 5: Selected Australian long-term sea level records (after BoM, 2007).

for local land movement and changes in atmospheric pressure, demonstrate a regional pattern of sea level trends that is consistent with sea level changes detected by satellite-based altimeters."

2.2.3 Latest IPCC Global Projections

The AR4 reports that there are now over 20 complex numerical Atmosphere-Ocean General Circulation Models (AOGCMs), which show increasing success in reproducing broad global climate behaviour. With higher resolution there has been reduced reliance on sub-grid parameterisation compared with the TAR. Important uncertainties remain, especially in regard to representation of cloud physics and feedbacks. These projections are based on a series of modelled greenhouse gas emission scenarios, which are predicated on world population estimates, economic growth and consequent energy usage patterns.

The most-often quoted scenario prior to the TAR was termed IS92a, which represented the "business as usual" outcome and implicitly assumed limited success of UNFCC plans to reduce emissions through international agreement. Following the IPCC (2000) Special Report on Emission Scenarios, a new set of 35 scenarios termed SRES was developed to replace the IS92 standard. These are also independent of UNFCC initiatives but attempt to describe a wider set of possible future world behaviours, leading to an increased range in emissions. The "A" class of SRES scenarios broadly represent an economic focus, while the "B" scenarios are more environmentally orientated. AR4 utilises a new set of experiments from 23 AOGCMs from the Coupled Model Intercomparison Project 3 (CMIP3) and the range of projected warming in the period 2090-2100, relative to 1980-1999, is based on the six SRES marker scenarios (B1, A1T, B2, A1B, A2 and A1FI). The often quoted mid-range future scenario is the A1B.

Land Surface Air Temperature

The likely range of surface air temperature increases based on the SRES marker scenarios varies between 1.1 °C and 6.4 °C centred on the decade 2090-2099 (herein referred to as 2095), with a range in means of 1.8 °C to 4.0 °C. It should be noted however that regional temperature changes are likely to vary substantially from the global mean value and the AOGCMs still show a relatively poor correlation in this regard. In broad terms, the Northern Hemisphere is expected to warm about twice the amount of the Southern Hemisphere, although Australia's increase is predicted to be above the global mean. It is also important to appreciate that surface temperature is projected to continue to increase beyond 2100 even if concentrations of greenhouse gases were stabilised by that time, because of the thermal inertia of the oceans.

Sea Level Rise

The central estimate is that sea level will rise by about 0.5 m by the year 2095, with a range from 0.18 m to 0.79 m.

The AR4 projections of global average sea level rise for 2095 (relative to the baseline of 1980-1999), using a range of AOGCMs that follow the SRES scenarios, lie in the range 0.18 m to 0.59m. The main contributions to this projected rise are thought to be, in order of decreasing contribution:

- an accelerating thermal expansion throughout the 21st century
- the melting of glaciers and ice caps
- retreat of the Greenland ice shelf.

AR4 expressed low confidence in ice sheet loss estimates generally, recommending a "scaled-up ice sheet discharge" allowance as a precautionary measure, with a nominal range of 0.1 m to 0.2 m on top of the above range, raising the upper estimate to 0.79 m. Current research activity in preparation for the IPCC 5th Assessment Report aims to enhance understanding of the effect of ice sheet loss on sea level rise.

Without the ice sheet allowance, the upper limit of these updated estimates represents a 33% reduction relative to IPCC (2001) and, with ice sheet uncertainty allowance, is about a 10% reduction. Overall, the upper level 2100 sea level rise estimate now is approximately 30% lower than the first IPCC estimate made in 1990. This continued slight reduction is considered to be due to improved modelling of glaciers and ice sheets, although the IPCC (2007a) notes that "…understanding of some important effects driving sea level rise is too limited" and "The sea level projections do not include uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. Therefore the upper values of the ranges given are not to be considered upper bounds for sea level rise". Furthermore, Church et al. (2008) note that "*While our understanding of the relevant processes is limited, it is important to recognise that the uncertainties are essentially one-sided. That is, the processes can only lead to a higher rate of sea-level rise than current projections.*"

A summary of these key projections of sea level increase by the year 2095 are presented in Table 1, which summarises the various projections to indicate the expected changes with time. In respect of regional variations, models agree on the qualitative conclusion that local changes may be substantial when compared with the global average. Beyond that, there is little similarity between the models in detail. Like temperature, nearly all models project greater than average sea level rise in the Arctic Ocean and below average rise in the Southern Ocean (Figure 6), although slightly higher than average values are indicated along the south-east coast of Australia and along a zonal band at around 30 °S to 45 °S. The latest advice on regional sea level rise projections for the Australian region is available on-line at the CSIRO sea level website http://www.cmar.csiro.au/sealevel/sl_proj_regional.html.

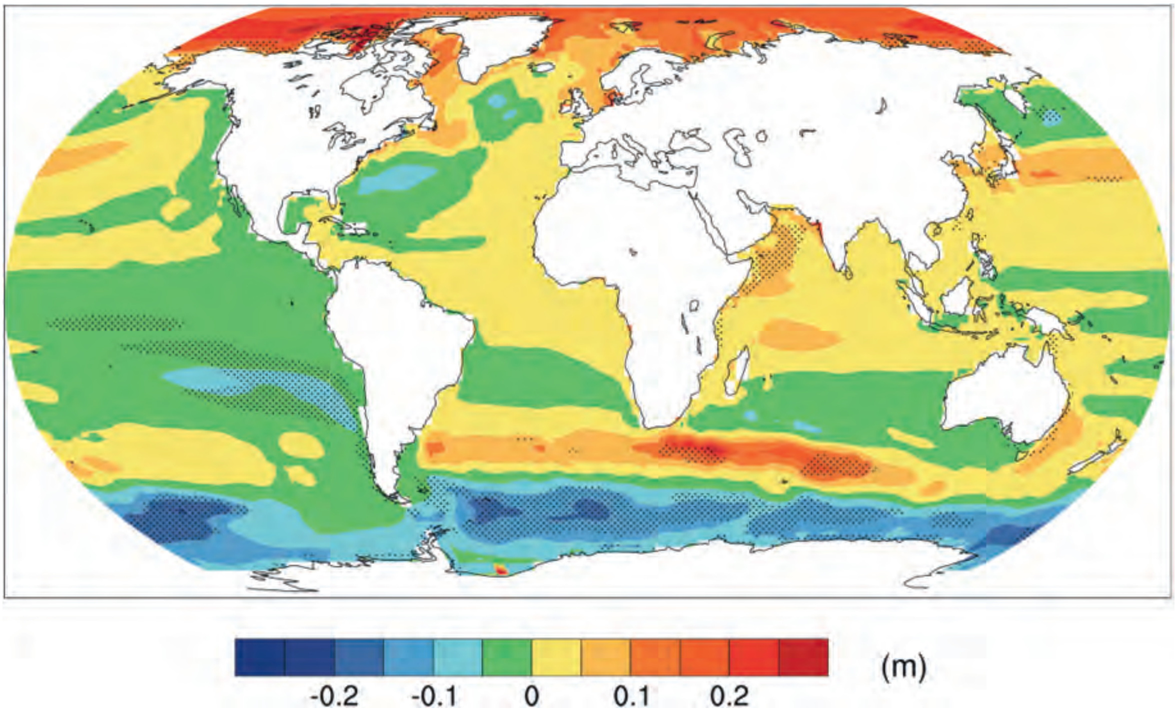

Figure 6: Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0. IPCC (2007b; fig 10.32).

Notwithstanding that 2100 is the targeted planning period here, it is important to note that if greenhouse gas concentrations were stabilised (even at present levels), sea level is nonetheless predicted to continue to rise for hundreds of years. By 2300, sea level rise from thermal expansion alone is likely to reach 0.3 m to 0.8 m relative to 1980-1999. Furthermore, if global average warming in excess of 1.9 °C to 4.6 °C persists for millennia, it is expected to lead to virtually a complete melting of the Greenland ice sheet, with a resulting global average sea level rise of about 7 m. There is enough capacity in the combined Greenland and Antarctic ice sheets to potentially raise global sea levels by almost 70 m IPCC (2007b).

Table 1: Projected sea level increases.

Scenario Range (m)	2095	2095 Plus Ice Caps
Min (5%)	0.18	0.28
Central (50%)	0.35	0.50
Max (95%)	0.59	0.79

Figure 7 shows the context of the above figures over time, based on the re-scaled TAR projections matching the new AR4 2095 values[3]. The recommended engineering estimates for 2100 are then a short extrapolation of the AR4 2095 values based on the TAR-derived slopes. The TOPEX/Poseidon decade of measurements is also included as a linear projection together with its uncertainty bands (for reference only).

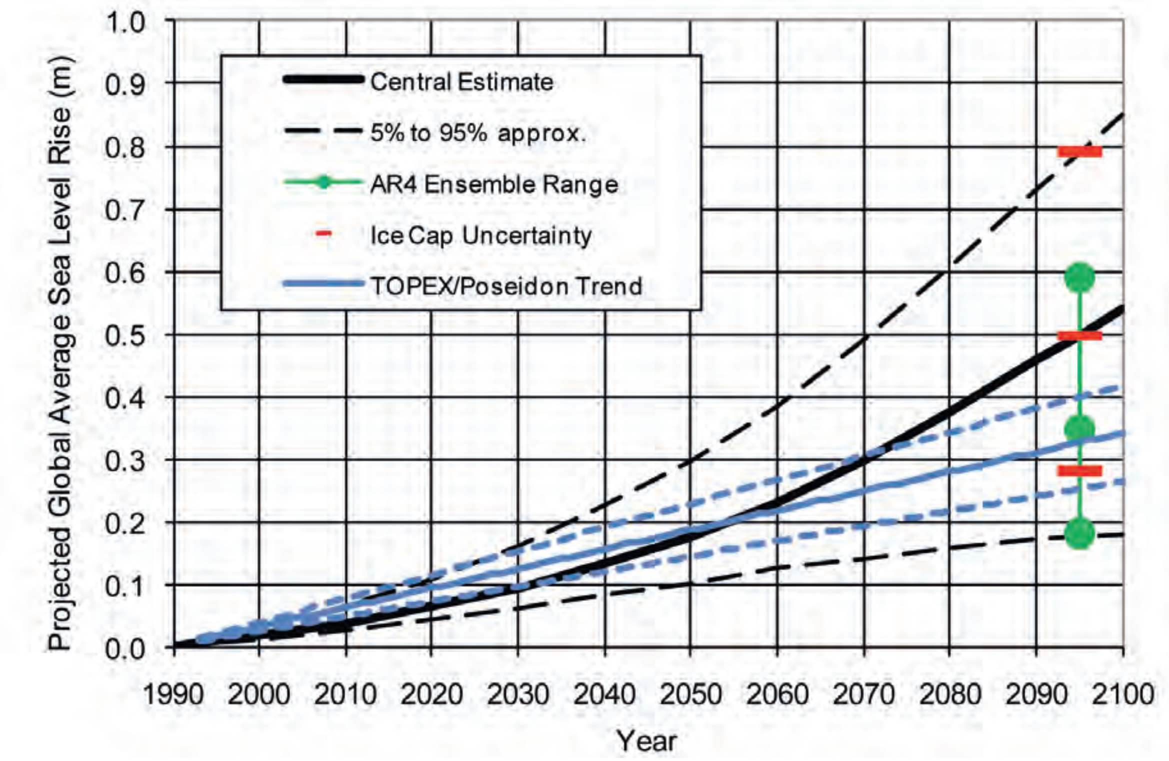

Figure 7: 1990 to 2100 SRES sea level rise projections (after IPCC, 2001b; 2007b).

2.2.4 Major Weather Systems and Global Climate Change

There are many complex interactions within the global climate system that are intrinsically linked to the deep ocean circulation. For example, the thermohaline circulation, with a timescale of many thousands of years, is a massive regulator of global temperature and is thought to play an important role in many other observed multi-decadal climate fluctuations (refer Section 2.3.2). However, the present discussion is limited to those features of typically decadal timescales or less, which are likely to have a more immediate impact on Australian climate.

El Niño – Southern Oscillation (ENSO)

The El Niño – Southern Oscillation (ENSO), which originates in the tropical Pacific Ocean, is one of the strongest natural fluctuations of climate on inter-annual timescales and is also believed to influence decadal timescales. ENSO is generated by ocean-atmosphere interactions such that positive sea surface temperature anomalies in the eastern equatorial Pacific (a so-called El Niño event) tend to reduce the normally high temperature difference across the Pacific. This results in a reduction of the easterly trade winds and a lowering of sea levels in the west and a rising in the east by as much as 0.25 m. During an El Niño, the Australian east coast typically experiences below-average sea surface temperature and the incidence of tropical cyclones is also significantly reduced as the zone

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[3] IPCC (2007) does not provide the projected sea level rise over time, only for the year 2095. Accordingly, the TAR (IPCC, 2001a) projections have been simply re-scaled here to match the new 2095 values. Similar approaches have been used in the literature, e.g. Hunter, 2009.

of tropical cyclogenesis typically moves more eastward. However, because of the oscillating ocean-atmosphere interactions a reverse phase or La Niña can also occur, whereby Australia experiences higher sea level and sea surface temperatures, with a greater incidence of coast-crossing tropical cyclones along the eastern seaboard.

The relative incidence of El Niño and La Niña episodes over the past 120 years typically suggests a chaotic system where the relative proportion of each extreme is similar. However, during the past two decades, there has been a much higher occurrence of El Niño events due to a general warming of the eastern Pacific. Some researchers believe that these recent changes (since 1976) may be attributable to climate change. However, this attribution is uncertain (IPCC, 2007b) in view of the strong natural variability and the inability of models to fully simulate ENSO realistically (e.g. Guilyardi et al., 2009). Nonetheless, AOGCMs project a continuation of the ENSO-like phenomenon under enhanced greenhouse conditions, with possible increases in precipitation variability over tropical regions.

Monsoons

The annual monsoon results from the seasonal large-scale overturning of the atmosphere in the tropics and sub-tropics. Rapid land heating draws low level maritime air inland where convection and release of latent heat causes a circulation to develop which, in addition to the large-scale precipitation, also causes a surge in the wind patterns in tropical areas.

It is likely that warming associated with increasing greenhouse gas concentrations will cause an increase of Asian summer monsoon precipitation variability. Changes in monsoon mean duration and strength depend on the details of the emission scenario. The confidence in such projections is limited by how well the climate models simulate the detailed seasonal evolution of the monsoons.

… future projections based on theory and high-resolution dynamical models consistently indicate that greenhouse warming will cause the globally averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2-11% by 2100. Knutson et al. (2010)

Tropical Cyclones

Any significant modifications to the behaviour of tropical cyclones (TCs) in a changed climate could have especially damaging impacts for some regions of northern Australia, especially closest to the present margins of TC exposure. In the context of coastal and ocean engineering, the potential exists for changing extreme wind, wave and current environments to perhaps adversely affect existing infrastructure where design conditions have been based on estimates from the historical dataset. In terms of loss of life, storm surges and their resulting storm tides represent the single greatest threat to our rapidly growing coastal populations (Harper, 1999; Dube et al., 2010).

In recent years there has been considerable debate in atmospheric science circles as to the role and behaviour of TCs in future climates. Early climate projections regarding TC changes (e.g. IPCC, 1998) were rejected by consensus from the expert tropical cyclone community in Henderson-Sellers et al. (1998) and that position was reflected in NCCOE (2004). Over time the consensus has shifted, notably prior to the 6th International Workshop on Tropical Cyclones (WMO, 2006a; 2006b) but continues to be monitored by the WMO Tropical Meteorology Research Programme TMRP Committee TC2 (Impact of Climate Change on Tropical Cyclones). The latest consensus view from that process is given by Knutson et al. (2010), summarised in part as follows:

- There is no definitive evidence at this time that (globally) TCs are getting stronger, or are becoming more frequent or producing greater rainfall. Some specific ocean basins are experiencing changes in frequency, which is not unusual on decadal time frames. The North Atlantic has seen recent decadal increases similar to levels experienced in the 1950s, while the Western North Pacific and parts of Australia have experienced fewer TCs than in the 1970s.
- The most intense TCs may have the opportunity to develop up to 11% stronger peak winds by

the year 2100[4] and the relative proportion of the most intense TCs would likely increase as a result (e.g. Category 4+).

- The global frequency of TCs may decrease by up to 34% due to a more unfavourable state of environmental shear. The extent of TC influence is not expected to greatly change.
- Rainfall rates are likely to increase in line with water vapour concentration. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone centre.

While the above assessment provides some reassurance against markedly changed threats from tropical cyclones, it must be appreciated that reliable design criteria for coastal and ocean structures throughout tropical Australia are still very limited. Much more work is needed to quantify these existing design risks, irrespective of future climate change scenarios. For example, Harper et al. (2008) demonstrates the need for review of historical tropical cyclone intensities in the Australian region.

Mid-Latitude Weather Systems

There is no compelling evidence to suggest that the characteristics of extratropical storms have changed and there is little agreement between models concerning future changes.

Notwithstanding weak evidence for possible changes in frequency or severity of intense large scale storms, there may be slight shifts in the mean seasonal synoptic patterns that could affect regional wind speeds and directions. This in turn could change the distribution of the wave-energy flux presently shaping the coastline.

2.3 Impacts, Adaptation and Vulnerability to Climate Change

2.3.1 General

These issues were addressed by Working Group II of the IPCC, focussing on a three tiered approach to the problem, *viz:*

1. How *sensitive* a particular system might be to climate change
2. How *adaptable* that system appears to be, and
3. How *vulnerable* the system ultimately is to climate change.

The AR4 has revised its previously developed common basis for expressing the uncertainty of the modelled projections:

Virtually certain	>	99% probability of occurrence,
Extremely likely	>	95%
Very likely	>	90%
Likely	>	66%
More likely than not	>	50%
Unlikely	<	33%
Very unlikely	<	10%,
Extremely unlikely	<	5%

In the oceans, climate change will be accompanied by changes in temperature, circulation, sea level, ice coverage, wave climate and possibly extreme events.

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[4] This is approximately equivalent to up to a 20% increase in central pressure deficit by 2100.

2.3.2 The Oceans

Oceans occupy about 70% of the earth's surface. They provide an important component of the climate system, due to their role in controlling the distribution and transfer of heat and CO_2 and in the transfer of freshwater back to the continents as precipitation. The oceans function as regulators of the Earth's climate and sustain planetary biogeochemical cycles. They have significant capacity to store heat and are the largest reservoir of the two most important greenhouse gases – water vapour and carbon dioxide. About 60% of the Earth's radiative energy from the Sun is received by the oceans, 80% of that being absorbed within the top 10 m.

Winds and waves mix down a seasonal surface layer of nearly uniform temperature, salinity and other properties that extends to tens of metres in the tropics and to several hundred metres in higher latitudes (the so-called upper thermocline). The permanent (lower) thermocline lies below the seasonal surface layer, down to about 1000 m. While wind-driven circulation dominates the upper ocean mixing, manifesting as basin-scale gyres and intensive western boundary currents, the deeper ocean circulation is controlled by thermohaline processes (density currents, internal waves, etc). The lower thermocline and abyssal ocean represents nearly 90% of the volume of the oceans and most of this water is colder than 5 °C. The oceans contain about 60 times more carbon than the atmosphere and variations in atmospheric carbon dioxide could result from even minor changes in the ocean's carbon cycling process, which is related to the ocean circulation. Conversely, carbonate chemistry dictates that the ocean is not an especially efficient sink for human-induced increases in atmospheric carbon dioxide concentrations (IPCC, 2001). Sea ice covers about 11% of the ocean and affects surface reflection of energy, salinity and ocean-atmosphere thermal exchange.

86% of Australians live in the coastal zone. (RAC, 1993)

In the oceans, climate change will be accompanied by changes in temperature, salinity, acidification, circulation, sea level, ice coverage, wave climate and possibly extreme events:

- Sea surface temperature (SST) increases are likely to be less than air temperature increases and to lag continental air temperature increases by as much as 10 years, before rising at a similar rate.
- Changes in SST gradients are expected to lead to a decrease in trade wind intensity, a reduction in strength of upper ocean currents and a decrease in areas and intensity of upwelling.
- Because of a lack of basic understanding of the present interactions, it is still premature to project the behaviour of ENSO events for different climate changes.
- Available estimates of future sea level rise are uncertain but will likely occur due to ocean thermal expansion, changing volumes of polar and glacial ice sheets, dynamical ocean circulation effects, altered wind and weather patterns and differences in regional ocean density.
- Even the lower estimates of global average sea level rise rates by 2100 are about 2 to 4 times the rate of sea level rise experienced in the last 100 years.
- Projected changes in climate could produce large reductions in the extent, thickness and duration of sea ice.
- Present numerical weather models suggest there is likely to be an increase in the intensity of the most severe tropical cyclones [refer Section 2.2.4] but that the frequency may reduce.
- Some corals are likely to be adversely affected through increased acidity, SST and SLR, possibly UVB exposure due to ozone depletion, leading to increased bleaching and a reduction in coral production.
- Many calcifying marine organisms and reefs would be disadvantaged by increased ocean acidity, which inhibits skeletal and shell growth, particularly for juveniles. Conversely, other species may have marginal advantage in these circumstances.
- Increased loading of land-based pollutants is expected as a result of increased precipitation and atmospheric transport.

2.3.3 Coastal Zones and Small Islands

It is estimated that 50-70% of the global human population (86% of Australians (RAC, 1993)) live in the coastal zone, where important socioeconomic activities include resource exploitation (living and non-living), industry and commerce, infrastructure development, tourism, recreation and nature conservation. In most coastal nations, a considerable part of gross national product is derived from activities connected with the coastal zone. Many coastal problems presently being experienced worldwide can be attributable to the unsustainable use and unrestricted development of coastal areas and resources. Climate change is likely to pose an additional stress on these areas, with sea level rise and possible changes in the frequency and intensity of extreme events being of prime concern. In addition to the physical changes that are possible, climate change has the potential to significantly affect coastal biological diversity through alteration of habitat.

The following are the major aspects of concern to the coastal zone and small islands:

- Any changes in sea level are expected to vary from the global mean over regional and local scales due to (i) vertical land movement e.g. subsidence, upheaval and (ii) dynamical ocean effects due to circulation patterns, wind and pressure distributions and density differences. These are effects that already dictate global variation in mean sea level but the possible changes caused by a warming climate are unknown at this stage.
- A 2 °C change in average SST would mean that values presently considered anomalous (of the order of peak ENSO fluctuations) could well be normal occurrences, with resultant long-term stress on natural ecosystems that are unable to effectively adapt.
- Increased precipitation is expected throughout the year in high-latitudes and during the winter in mid-latitudes, possibly increasing coastal deposition rates. Some increase in Asian monsoon rainfall is also predicted.
- Changes in storm patterns or general shifts in mean weather conditions (windiness, wave energy and direction) are not able to be reliably estimated at this time but could have significant long term impacts on coastal stability and alignments (e.g. Slott et al., 2006).
- Any potential increase in the frequency, magnitude or extent of very severe weather systems such as tropical cyclones could severely impact some coastal regions, with the potential for loss of life and significant impacts on coastal ecosystems and morphology. The present projections show a low likelihood of significant changes occurring for tropical and extra tropical cyclones. Low reef-fringed islands may also be especially susceptible to any increase in the magnitude of wave-induced setup (e.g. Gourlay, 1997).

The possibility of sea level rise alone forms a basis for considering a number of major impacts for the coastal zone, such as:

- inundation and displacement of wetlands and lowlands
- eroded shorelines
- increased coastal flooding by storms
- salinity intrusion of estuaries and aquifers
- altered tidal ranges, prisms and circulation in estuarine systems
- changed sedimentation patterns
- decreased light penetration.

While it is instructive to devise relatively simple models of land-sea boundary shifts based on water level changes alone, the actual impacts of sea level rise at specific locations are likely to be very complex. For example, the responsiveness of geomorphological and ecological processes will largely dictate the local outcomes, necessitating a consideration of the specific coastal environments that are at risk, e.g:

Sedimentary coasts, sandy beaches, barriers and dunes

- About 20% of the world's coasts meet this general classification (24% of Australia). The short to medium term dynamics of these types of coasts have been extensively studied by coastal engineers and a range of modelling tools are available. In spite of this, it still remains an area of considerable uncertainty in quantitative terms. In the longer term, availability and rate of sediment supply remain largely unknown and geological timescale analyses (e.g. Holocene stratigraphical reconstructions) represent relatively slowly varying scenarios relative to present sea level rise predictions.
- It is likely that under future sea level rise, there will be a tendency for currently eroding shorelines to erode further, stable shorelines to begin to erode and accreting coasts to wane or stabilise (e.g. Bruun, 1962).

Deltaic coasts, estuaries and lagoons

It is likely that under future sea level rise, there will be a tendency for currently eroding shorelines to erode further, stable shorelines to begin to erode and accreting coasts to wane or stabilise.

- Deltaic coasts are particularly susceptible to any acceleration in the rate of sea level rise and storm frequency and intensity. Most major delta regions of the world are already subsiding through consolidation of sediment, have highly developed infrastructure and are heavily populated. Submergence is clearly likely under an increasing sea level scenario and progradation of deltaic coastlines will likely be curbed through increased erosion, except in those areas where sediment supply may increase due to increased precipitation.
- In river and estuary systems changes in mean water level may affect tidal propagation (range and prism effects) and changed circulation patterns are possible that will modify sedimentation processes. Saltwater penetration will increase, raising groundwater levels and may have adverse impacts on freshwater extraction from some coastal aquifers.

Coastal wetlands

- Coastal wetlands are normally associated with deltas and estuaries. Any loss of sediment supply and increase in wave energy may therefore have impact on these environments in a significant way. Loss of seaward boundaries of salt marshes and mangrove forests may result in major loss of ecosystem and natural foreshore buffering where it has been backed by land-based construction for flood protection or other defences. In still-natural environments there may be some opportunity for landward migration at a rate commensurate with sea level rise, depending on the sediment supply.
- The behaviour of seagrasses extending sub-tidally is less well predicted.

Coral reefs and reef islands

- Coral reefs and reef islands appear especially susceptible to climate change and associated sea level rise and increased ocean acidity. The impacts on these systems can be best divided into biological and physical. For many low lying coral atolls, the physical changes as a result of sea level rise are perhaps the most immediate threat. Higher sea levels over the next century will increase erosion of the coastline, inundation and flooding of low lying areas and seawater intrusion into groundwater lenses and hence reduce the habitability of these islands. However, individual responses are likely to vary greatly as a result of sediment availability, present elevation, aquifer characteristics and general resilience of the natural systems.
- The biological systems that support these islands in terms of sediment supply and ecosystem services for the inhabitants are most threatened by changing ocean chemistry and temperature rather than sea level rise. Significant climate change impacts on corals are expected to be caused by warmer sea surface temperatures and increasing ocean acidification. Coral bleaching

occurs when SST rises above a certain threshold; an annual or bi-annual exceedance of bleaching thresholds is projected for most coral reefs by 2030-2050. It is estimated that warm water coral cover has reduced globally by about 30% or higher in recent decades due to more frequent exposure to high SST (Wilkinson, 2004; Hoegh-Guldberg, 2005). Additionally, ocean acidification reduces rates of coral calcification, weakening coral skeletons and causing erosion of reef frameworks. The sensitivity of corals to these impacts may inhibit their ability to cope with other environmental changes. Indeed, many coral reef areas are already thought to be adversely affected by elevated sediments and nutrients from rural and urban runoff, which may also increase in some areas under a changed climate[5].

2.4 Possible Response Strategies

2.4.1 Adaptation Options

The Options:

Retreat …

Accommodate …

or

Protect …

The IPCC process identified the four major areas of concern regarding sea level rise as:

- inundation and increased flooding of low-lying islands
- inundation and increased flooding of densely populated deltaic areas
- loss of coastal wetlands, their ecosystems and protective physical buffering
- erosion of developed sandy coasts.

There is potentially a wide array of adaptation options that can be employed in response to actual climate change threats. The IPCC presents a simple set of three strategy options, namely retreat, accommodate or protect, often called the adaptation hierarchy, which serve to illustrate the basic range of possible responses:

1) Retreat

Emphasis is on abandonment of land and structures in highly vulnerable areas and resettlement of inhabitants, e.g:

- preventing development in areas near threatened coastal areas
- conditional approvals and phasing-out of development
- withdrawal of government subsidies.

2) Accommodate

Emphasis is on conservation of ecosystems harmonised with the continued occupancy and use of vulnerable areas and adaptive management responses, e.g:

- advanced planning to avoid worst impacts
- modification of land use, building codes
- protection of threatened ecosystems
- strict regulation of hazard zones
- hazard insurance.

3) Protect

Emphasis is on defence of vulnerable areas, population centres, economic activities, infrastructure and natural resources, e.g:

- hard structural options such as:
    - dykes, levees, flood barriers
    - sea walls, revetments, groynes
    - saltwater intrusion barriers.

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[5] This passage has been adapted from the IPCC AR4 Working Group II report on impacts on coral reefs.

- soft structural options such as:
    - beach nourishment
    - dune restoration
    - wetland creation
    - littoral drift make-up
    - afforestation.

The choice of adaptation will vary greatly depending on the circumstances of the threat, the vulnerability of the region, the ownership or tenure of the affected land and the capacity of the responsible authority or nation. Adaptation can exploit the fact that coastal infrastructure is rarely static and will undergo major refurbishment or replacement on time scales of 25 to 30 years, thus providing many opportunities to adapt structurally. Maintaining the security and integrity of the land on which the development and infrastructure lies requires up-front long-term consideration. However, early allowance in design, development approvals and planning will significantly reduce the total cost to the community and provide sustainable or even enhanced environmental outcomes. It should be noted though, that sea levels might continue to rise above those predicted by present day scenarios.

2.4.2 Implementation

The threats of possible climate change upon the coastal zone have similar implications to the more direct impacts of human development pressures on the coastal environment, which are already measurable through increased pollution, loss of habitat or altered ecosystems.

The evolving philosophy of Integrated Coastal Zone Management (ICZM) already has the capacity to provide appropriately managed and planned solutions to these direct human impacts and the indirect threats of climate change. ICZM can provide an environment for comprehensive assessment, setting of objectives, planning and management of coastal systems and resources, while taking into account traditional, cultural, and historical perspectives and conflicting interests and uses.

Some of the essential prerequisites for effective ICZM are:

- initial leadership for the planning process
- provision of institutional arrangements
- technical capacity, and
- management instruments and tools.

A proactive approach to ICZM is a key component for accommodating the long term effects of climate change and NCCOE (2004b) provides advice on such matters within the overall context of ecologically sustainable development of the coastal zone. The coastal and ocean engineer has the technical capacity and practical approach necessary to ensure effective planning methodologies are adopted within this context, thus providing an essential leadership role.

There are a number of references that may provide additional guidance on these and related matters, e.g. Burby & Nelson (1991) for US experience and approaches, McLean & Mimura (1993) and Nicholls et al. (1995) discuss vulnerability assessment methodologies, Hoesner & Chung (1997) address natural disasters, Watts (1997) gives a reasonably comprehensive engineering overview of climate change for coastal vulnerability studies. Some economic analyses and implications are also available, e.g. Barth & Titus (1984), Titus (1984). JCR (1995) and Milliman & Haq (1996) present numerous case studies for major delta regions such as Thailand, India, Bangladesh, China, Egypt, Italy, Africa, Europe, South America and the USA. Wind (1987) and Peerbolte (1993) provide policy analysis and modelling strategies. The latest globally relevant studies are accessible through IPCC (2007c) and Section 3 indicates various specific Australian studies.

3 . THE AUSTRALIAN CONTEXT

3.1 Research Environment

CSIRO Marine and Atmospheric Research (CMAR) has traditionally provided the majority of climate change assessment and prediction capability for the Australian Government, although the Bureau of Meteorology (BoM) National Climate Centre (NCC) and the Centre for Australian Weather and Climate Research (CAWCR, previously BoM Research Centre or BMRC) has developed a strengthened joint role (e.g. Whetton et al., 2005; CSIRO-BoM, 2007). Many more organisations contribute to scientific assessment of observations and impacts, these include Geoscience Australia, the BoM National Tidal Centre (NTC, previously the National Tidal Facility at Flinders University of South Australia), various Federal and State government departments (typically with Climate Change, Environment or Primary Industry responsibilities) and numerous university-based researchers and some private consultants. The Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC, comprising The University of Tasmania and CSIRO) additionally provides sea level projections and analyses. The Australian Government coordinating body for climate change matters is the Department of Climate Change and Energy Efficiency, which produces and commissions a wide range of materials in regard to the state of the science, impacts and adaptations (e.g. Allen Consulting, 2005; NRMMC, 2006; DCC, 2009a; 2009b).

As the science of climate change is continually changing, the latest published sources should always be sought for use in any detailed studies[6]. All regional projections must still be viewed within the context that, relative to their assessed global performance, climate models are considered to still have significantly reduced skill at sub-continental scales. Where available, local data and records should always be sourced and reviewed.

3.2 Coastal and Ocean Impact Studies

Australia has a strong research background in climate change and associated oceanographic and atmospheric phenomena. For example, McInnes et al. (1992) and Hopkins & Holland (1997) on east coast lows and rainfall; Evans et al. (1994) on tropical cyclone rainfall, may be relevant to a specific impact assessment. Walsh & Katzfey (2000), Walsh & Ryan (2000) and Walsh et al. (2004) consider possible changes in regional tropical cyclone characteristics.

For reasonably general and broad overviews of impacts and vulnerability, Pearman (1988) and its update Bouma et al. (1996) and Basher & Pittock (1998) are still useful compendiums, albeit with now outdated projection information. More recently, Ryan et al. (2003), Walsh (2004), Voice et al. (2006), AGO (2006), Abuodha & Woodroffe (2007), Harper (2008), Harvey & Woodroffe (2008) and Woodroffe (2008) provide frameworks and overviews of interest to the coastal and ocean context. Heap et al. (2001) and Harris et al. (2002) consider ecosystem management and classification of coastal environments. Attwater et al. (2008) consider adaptive responses in a planning context and Sharples et al. (2008) presents a tiered approach to risk assessment. Ranasinghe & Stive (2009), Ranasinghe et al. (2007; 2009a; 2009b) and Stive et al. (2009) focus on sea level rise and coastline recession. Callaghan et al. (2008a; 2008b) present methods to derive probabilistic estimates of storm erosion for coastal planning. McInnes et al. (2007) and Hemer et al. (2008; 2009) considers climate change driven variations in the offshore wave climate and implications for coastal vulnerability.

In regard to storm surge, the Queensland Climate Change Study (Harper, 2001; 2004) provides technical recommendations and specific projections of changing risks along the East coast for tropical

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[6] http://www.climatechange.gov.au ; http://www.bom.gov.au/climate/change/ ; http://www.climatechangeinaustralia.gov.au/ ; http://www.cmar.csiro.au/sealevel/sl_proj_regional.html.

cyclone conditions and McInnes et al. (2003) consider a specific scenario for Cairns. Harper et al. (2009) provides a summary of a range of potentially relevant Australian studies and there are many Local Government commissioned studies (refer Section 8). For non-cyclonic impacts Church et al. (2006) and recent ACE CRC publications are valuable where tidal records are sufficiently long.

3.3 Government Policies

This remains an area of significant flux and readers should ensure that they have the latest relevant information in this regard. Table 2 below summarises known Government policies as of October 2010. These will continue to be revised and the practitioner should familiarise themselves with the latest jurisdictional position.

Table 2: Sea level rise allowances relative to 1990 base level for each Government constituency at 30th October 2010.

Jurisdiction	2050	2100	Comment / Basis
	m	m	
Commonwealth		1.1	Adopted for national vulnerability assessment DCC (2009b) http://www.climatechange.gov.au/en/publications/coastline/climate-change-risks-to-australias-coasts.aspx
New South Wales	0.4	0.9	Benchmark levels, Sea Level Rise Policy Statement DECCW (2009a) http://www.environment.nsw.gov.au/climateChange/sealevel.htm
Northern Territory			0.8 m by 2100 is understood to be under consideration.
Queensland		0.8	Draft coastal policy DERM (2010a) http://www.derm.qld.gov.au/coastalplan/pdf/coastal_plan_guide_coastal_hazards.pdf
South Australia	0.3	1.0	Policy on coast protection and new coastal development 1991 http://www.environment.sa.gov.au/Conservation/Coastal_Marine/Coast_Protection_Board/Policies_strategic_plans
Tasmania	–	–	Sea Level Rise planning benchmarks are under consideration and development of policy in this area is a priority for 2011.
Victoria		0.8	Victorian Coastal Strategy 2008. “A policy of planning for sea level rise of not less than 0.8m by 2100 should be implemented”.
Western Australia	–	0.9	0.9m for a 100 year period (2010-2110) based on upper bound (95th percentile) of the IPCC AR4 SRES scenario A1FI including the allowance for “scaled-up ice sheet discharge”.

4. ENGINEERING IMPACT ASSESSMENT

4.1 Scope

Coastal and ocean engineering covers a wide range of activities, often with practitioners developing further expertise in specific areas. The following guidelines have attempted to encompass this wide range, characterised by the summary in Table 3 below, which is classified according to the operating environment, i.e. offshore, nearshore, beach and shoreline, and estuary and tidal lake. It is possible that the same activity, for example a marina, may require a different response to climate change impacts depending on the environment in which it is constructed.

Table 3 – Coastal and ocean engineering activities that may be affected by climate change.

Offshore (>60m)	Nearshore	Beach and Shoreline	Estuary and Tidal Lake
Anchor Systems	Aquaculture	Artificial Surfing Beaches	Aquaculture
Deepwater Mining	Coral Reef Environments	Beach Management	Boating Facilities
Ocean Outfalls	Breakwaters	Beach Mining	Bridges
Pipelines	– Fixed	Beach Nourishment	Canal Estates
Structures	– Floating	Beach Stability	Channel Stability
– Fixed	Dredging and Disposal	Boating Facilities	Causeways
– Floating	Extractive Industry	Coastal Zone Management	Development
Risers	Marinas	Development	– Commercial
Submarine Cables	Marine Parks	– Commercial	– Industrial
Subsurface Facilities	Mooring Systems	– Industrial	– Infrastructure
Tethered Systems	Navigation Aids	– Infrastructure	– Residential
Towing Systems	Navigation Channels	– Residential	– Tourist
	Offshore Disposal	– Tourist	Dredging and Disposal
	Outfalls	Groynes	Entrance Management
	Ports and Harbours	Marinas	Estuary/Lake Management
	Power Station Cooling	Reclamation	Flood Mitigation
	Reclamation	Revetments	Marinas
	Sediment Processes	Sand By-Passing	Mining
	Stormwater Disposal	Sediment Transport	Navigation
	Structures	Structures	Power Station Cooling
	– Fixed	– Fixed	Reclamation
	– Floating	– Floating	Shore Stability
	Underkeel Clearance	Vegetation Protection	Stormwater Disposal
	Wharves/Jetties	Stormwater Outlets	Structures
			– Fixed
			– Floating
			Submarine Crossings
			Tidal Barrages
			Training Works
			Vegetation Protection
			Water Quality Control
			Wetland Management

4.2 Methodology

The recommended methodology for assessment is to consider the relative likely importance of changes to the key environmental variables that have been the subject of climate change scenario modelling, and then to consider possible secondary effects that may flow from these primary changes.

The key environmental variables are considered to be:

- mean sea level
- ocean currents and temperature
- wind climate
- wave climate
- rainfall / runoff
- air temperature.

These key climate change variables are listed in Table 4, together with a summary statement of the respective climate change scenario for Australia, as discussed in previous sections.

The methodology then considers the potential impacts of changes in these primary variables to a selection of secondary variables of relevance to coastal and ocean engineering. The adopted secondary variables (also perhaps termed *process* variables) are presented in Table 5. The likely interactions between the primary and secondary variables are explored in Table 6 for guidance. Those interactions assessed as being particularly significant have been shaded to assist interpretation of the table.

In most instances an experienced coastal and ocean engineer will be able to quantify the climate change to secondary variables through knowledge of the physical interactions. However in some instances, e.g. coastal recession due to sea level rise, interactions may be highly complex and established procedures may not be appropriate to the site or may provide little more than guidance. In such instances, the professional engineer will need to exercise judgement in testing for sensitivity and applying safety factors to take account of uncertainty. A suggested procedure for making these necessary assessments follows below.

4.3 Application

Given the present uncertainties regarding the impact of climate change on factors affecting coastal and ocean engineering the recommended approach is one of combined risk and sensitivity analysis. Figure 8 provides a flowchart summary of the following recommended procedure for engineering assessment:

The design life of the facility or planning horizon of the activity … underpins the design philosophy and may fundamentally control the selection of material, methods and expertise.

Step 1: Specify the Design Life or Planning Horizon

This is a decision taken in consultation between the professional engineer and the client (government, industry or private), based on advice from the engineer regarding practicality, serviceability and cost of the envisaged facility and the client requirement for level of performance, term of operation and budget. The design life of the facility, or planning horizon of the activity, should be understood and agreed by all stakeholders because it underpins the design philosophy and may fundamentally control the selection of material, methods and expertise. Potential climate change considerations may influence this decision. Change of land use (e.g. from rural to residential) may have implications under the planning process and in common law that extend significantly beyond the design life of an individual structure (or dwelling) constructed on the property.

Step 2: Examine the Consequences of Failure

The impact of the possible "failure" of the facility (e.g. structure, process or management strategy) will have direct and indirect consequences, and should be assessed in terms of primary risk outcomes as issues of cost, safety and environment.

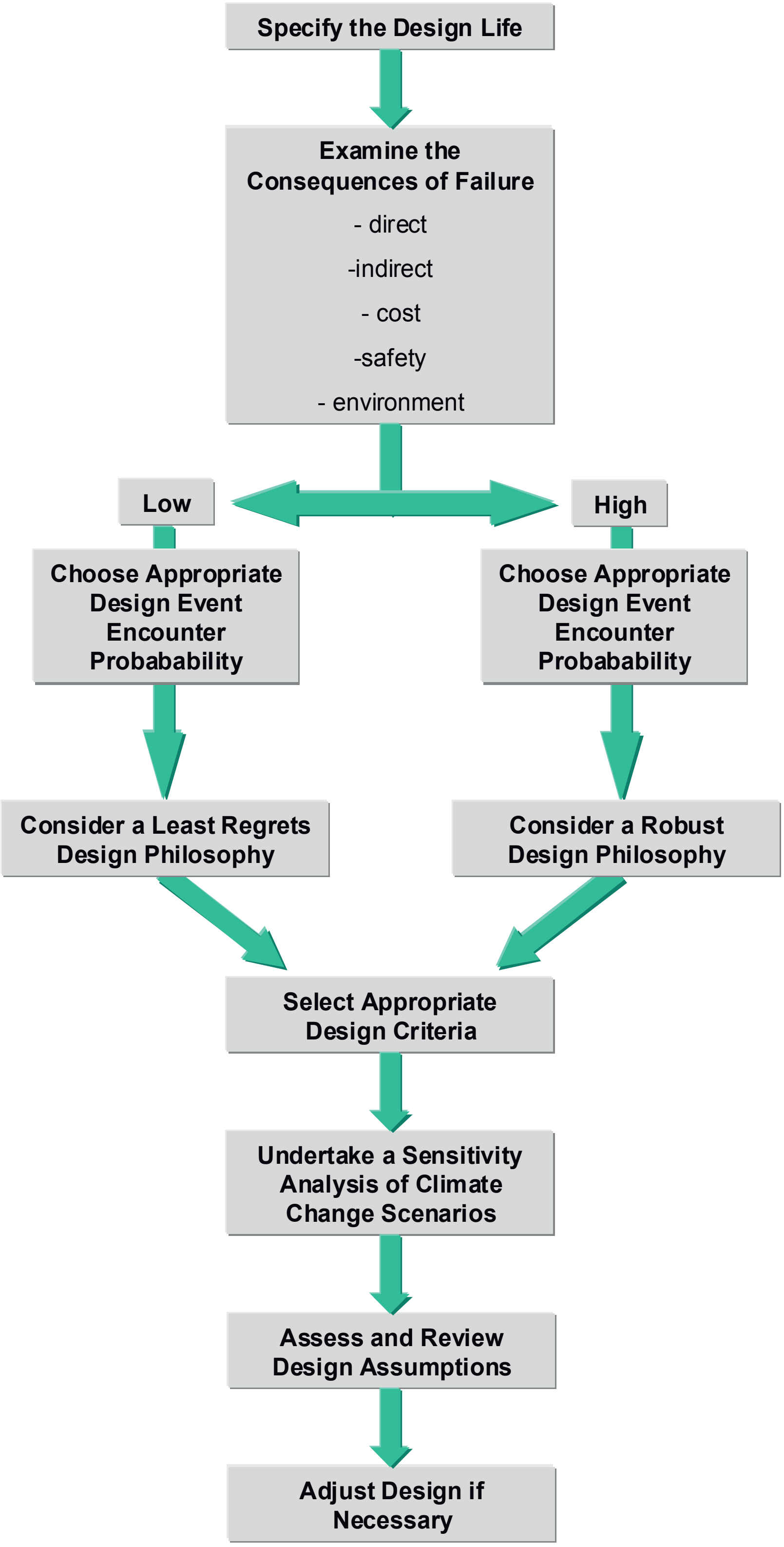

Figure 8: Recommended engineering impact assessment procedure.

Table 4: Key environmental variables and climate change scenarios.

Key Variable	Code	Australian Scenario	Comment
Mean Sea Level	**K1**	Projected range of sea level rise (m): **Year 2050 2100** Min (5%) 0.10 0.20 Central (50%) 0.20 0.55 Max (95%) 0.30 0.85 (See Figure 7)	Global average sea level rise scenarios must be converted to estimated local relative sea level movement for each site. Local effects due to changing dynamic heights may also vary. Government policy and guidelines must be taken into account.
Ocean Currents and Temperature	**K2**	No quantitative or qualitative models are available for coastal regions of the continent. Important to differentiate between currents driven by major circulation, e.g. East Australian or Leeuwin Current and atmospherically forced currents such as storm surge or coastally trapped waves. Tidal currents will vary in shallow waters with sea level rise. SST increase similar to air temperature increase.	Natural spatial and temporal variability still masks the underlying behaviour of the oceans and hinders climate change assessment. Global data gathering is advancing knowledge on many fronts.
Wind Climate	**K3**	***Largely qualitatively:*** – Trade winds may be weaker – Westerly wind stream may move further south. ***More quantitatively:*** – Maximum potential intensity of tropical cyclones may increase by 10% to 20% by 2100 – Regions of cyclogenesis and the regions affected by tropical cyclones are not expected to change significantly – Fewer tropical cyclones are possible in some regions.	Climate models do not at this stage provide firm predictions for any key meteorological features such as the timing, intensity or location of the tropical monsoon, mid-latitude systems, the subtropical anti-cyclone belt or ENSO related effects. Localised effects remain possible.
Wave Climate	**K4**	Regional mean wave climate will alter if regional mean wind patterns change. Seasonal wave direction would be affected if the mean latitudinal position of major weather systems alone were changed. Other factors will be site specific and determined by the local sea level rise and bottom topography.	Not possible to formulate a general scenario for all of Australia as effects could vary regionally. Intensity changes are subject to qualifications in regard to the wind climate.
Rainfall / Runoff	**K5**	***Rainfall changes:*** – refer CSIRO-BoM (2007) – Australian Rainfall and Runoff (Pilgrim, 1987) is currently under revision.	Increases are possible in the magnitude of high-intensity precipitation events while the frequency of occurrence is likely to be lower.
Air Temperature	**K6**	***Rise in land surface air temperature:*** ***By 2030:*** – 0.7-0.9 °C coastal areas ***By 2070:*** – refer CSIRO-BoM (2007).	Increases are possible in the frequency of occurrence of extremely high temperatures with reductions in the frequency of very low temperatures.

Table 5: Secondary or process variables.

Secondary Variable	Code
Local Sea Level	S1
Local Currents	S2
Local Winds	S3
Local Waves	S4
Effects on Structures	S5
Groundwater	S6
Coastal Flooding	S7
Beach Response	S8
Foreshore Stability	S9
Sediment Transport	S10
Hydraulics of Estuaries	S11
Quality of Coastal Waters	S12
Ecology	S13

The "failure" of the facility will depend on its inability to perform its intended function. This may have several dimensions for a complex facility and does not always simply imply "structural failure beyond repair", although that might be the ultimate consequence. The "failure" needs to be linked to the possible combination of factors or events (natural or manmade) that would cause the defined failure condition(s) to occur.

The possibility of "failure to perform intended function" must consider cost, safety and environmental issues.

Step 3: Select the Design Event Encounter Probability

This quantifies the acceptable risk of "failure" of the facility for the duration of the chosen design life or planning horizon and should be based on the assessed consequences of failure, in its various dimensions. All stakeholders should agree to the adopted level of risk and understand its potential consequences. For complex facilities, differing encounter probabilities might be entirely appropriate for separate elements of the design, provided the interactions are properly assessed.

Where the consequence of failure has been assessed as relatively "low", it might be appropriate to consider a relatively higher probability of encounter with the design failure condition(s). This would only be appropriate where the risk to life, property and the environment is very low and where there is a significant overall cost advantage in this strategy (remembering that repair and replacement costs will also need to be assessed).

Where the consequence of failure has been assessed as relatively "high", it would be appropriate to consider a relatively lower probability of encounter with the design failure condition(s). This may be dictated by a primary safety concern, a significant environmental impact or an unacceptable business loss condition.

Step 4: Follow an Appropriate Design Philosophy

For a low consequence of failure (high encounter probability) the appropriate design philosophy might be characterised by a least regrets strategy. This acknowledges that "failure" of the facility will probably occur and the design process should concentrate on amelioration of the impact of failure from the most sensitive aspect(s), e.g. the ability/cost to repair or replace or the environmental impact, whether visual or actual.

Table 6: Relationships between key and secondary variables.

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Local Sea Level S1						
Astronomical Tide	Major direct effect especially in estuaries and tidal lakes	Minor effect	No direct effect	No effect	No effect	No effect
Barometric Tide	Minor effect	Minor density effect	Weather system track related	No effect	No effect	Indirect through air pressure
Storm Surge	Greater overland penetration; possible bathymetry effect changes	Indirect effect of prevailing currents, SST	Major direct effect	Minor effect	Flood coincidence effects via tailwater	No direct effect
Wave Setup	Altered refraction	Minor effect	Indirect effect	Major direct effect	Possible interaction via tailwater	No effect
Trapped Coastal Waves	Minor effect	Unknown effects	Dependent on changes in major wind systems	Minor effect	No effect	No effect
Tsunami	Minor effect	Minor effect	No effect	No effect	No effect	No effect
Local Currents S2						
Tidal Stream	Major direct effect in estuaries and tidal lakes	Minor effect	No direct effect	No effect	No effect	No effect
Wind Driven	Direct effect	Minor effect	Direct effect	Minor effect	No effect	No effect
Wave Driven	Possible major direct effect in some shallow water regions, especially reefs	Minor effect	Indirect effect	Major direct effect	No effect	No effect
Density Driven	May be affected relative to natural sills in estuaries	Baroclinic ocean currents may be affected	May be affected by surface mixing	May be affected by surface mixing	May be impacted by runoff in estuary or nearshore areas	May affect stratification in nearshore areas
Prevailing	Minor effect	Major direct effect	Major direct effect	No effect	Minor effect	No effect
Storm Surge	Major direct effect in shallow water regions	Minor effect	Major direct effect	Minor effect	No effect	No effect

Table 6: Relationships between key and secondary variables (continued).

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Local Winds S3						
Prevailing	No effect	Minor effect	Major direct effect	No effect	No effect	Minor effect
Sea Breeze	Minor effect	Minor effect	Minor effect	No effect	Minor effect	Possible effect on magnitude
Storm	No effect	Minor effect	Major direct effect on frequency, magnitude and possibly direction	No effect	No effect	Minor effect
Local Waves S4						
Wind Driven	Possible major effect in shallow water regions	Minor effect	Direct effect	Indirect effect	No effect	No effect
Prevailing Swell	Possible major effect in shallow water regions	Minor effect	Indirect effect	Major direct effect	No effect	No effect
Extreme	Possible major effect in shallow water regions	Minor effect	Indirect effect	Major direct effect	Possible flood interaction	No effect
Effects on Structures S5						
Investigation	Minor effect	Changing statistics will affect determination of design criteria	Changing statistics will affect determination of design criteria	Changing statistics will affect determination of design criteria	Changing statistics will affect determination of design criteria	No effect
Design	Major direct effect	Minor effect	Major direct effect on forcing; possible changes to marginal probability of failure	Major direct effect on forcing; possible changes to marginal probability of failure	Major effect depending on location or purpose	Minor effect
Construction	Minor effect	Minor effect	May affect downtime	May affect downtime	Minor effect	Minor effect
Operation	Major effect for older structures	Minor effect	May impact depending on function	May impact depending on function	Minor effect	Minor effect
Maintenance	Minor effect	Possible increased marine fouling rates	Older structures may need retrofitting or upgrade	Older structures may need retrofitting or upgrade	Minor effect	Possible increased corrosion rates
Removal	Minor effect	Minor effect	May affect downtime	May affect downtime	Minor effect	Minor effect

Table 6: Relationships between key and secondary variables (continued).

	Mean Sea Level K1	Ocean Currents & Temperature K2	Wind Climate K3	Wave Climate K4	Rainfall / Runoff K5	Air Temperature K6
Groundwater S6						
Level	Major direct effect	No effect	Indirect effect	Local setup changes may occur	Direct effect	No effect
Quality	Saltwater intrusion possible	No effect	No effect	Minor effect	Minor effect	
Quantity	Reduced storage	No effect	No effect	Minor effect	Affects phreatic surface	Minor effect
Flow rate	Hydraulic gradients may reduce	No effect	No effect	No effect	Affects hydraulic gradient	Possible minor increase in transmissability
Coastal Flooding S7						
Level	Major direct effect; tailwater increases on river runoff and site drainage	No effect	Major direct effect via intensity of severe storms and cyclones	Major direct effect via wave setup at open sites	Direct effect via changes in intensity of rainfall	No effect
Frequency	Major direct effect	No effect	Major direct effect via frequency of severe events	Major direct effect via wave setup at open sites	Direct effect via changes in frequency of rainfall	No effect
Extent	Major direct effect	No effect	Major direct effect via distribution of severe events	Major direct effect via wave setup at open sites	Direct effect via changes in rainfall distribution	No effect
Beach Response S8						
Alignment	Effects due to changed wave refraction, diffraction and attenuation (under high SLR scenarios only)	Possible wave-current refraction interaction	Aeolian transport processes; dune stability; vegetation changes; longshore currents	Wave directional energy changes, directional storm occurrence statistics	Estuary discharges; storm-water drains; seasonal changes in sediment supply; vegetation; dune stability	Vegetation changes; sea breeze effects
Recession or Progradation	Recession with sea level rise	Possible wave-current refraction interaction; changes in long term sediment supply	Net change to sediment budget possible	Wave directional energy changes	Estuary discharges; storm-water drains; seasonal changes in sediment supply; vegetation; dune stability	Vegetation changes; sea breeze effects

Table 6: Relationships between key and secondary variables (continued).

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Fluctuations	Effects due to changed wave refraction, diffraction and attenuation; wave setup and runup	Possible wave-current refraction interaction	Changed timescales for beach recovery	Wave directional energy changes; changed timescales for beach recovery	Estuary discharges; storm-water drains; seasonal changes in sediment supply; vegetation; dune stability	Vegetation changes; sea breeze effects
Foreshore Stability S9						
Reef	Wave penetration; changed coral regeneration rates	Changed coral nutrient supply	Wind generated reef currents	Changed impact energy; wave direction and setup	Changed coral growth rates	Changed coral growth rates
Entrance	Tidal prism changes; flow velocities; bar configuration; entrance channel configuration	Minor effect	Changed nearshore currents affecting sediment transport; aeolian transport	Changed littoral drift environment	Frequency of break-out; baseline flows	No effect
Dune	Groundwater level affecting stability, wave setup wave runup; increased wave exposure and beach fluctuations; possible dune overtopping	Minor effect	Changed dune shape, mobility, vegetation, alignment; dune blowout	Changed scarp toe erosion; wave runup and overtopping; break through	Elevated phreatic levels; pore pressure changes; vegetation	Vegetation changes
Bluff (plus indurated sand)	Exposure of sediments to water based erosion	Minor effect	Changed vegetation; direct wind erosion	Changed scarp toe erosion; wave runup	Changed pore pressures; vegetation; weathering; frictional properties	Vegetation changes; weathering
Cliff	Exposure of sediments to water based erosion	Minor effect	Changed vegetation; direct wind erosion	Changed impact energy; wave runup	Surface weathering; erosion	Vegetation changes; rate of chemical weathering

Table 6: Relationships between key and secondary variables (continued).

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Sediment Transport S10						
Longshore	Changed distribution of motive energy; breaker depth; wave refracted angle	Magnitude and duration of storm currents	Longshore wind generated currents	Wave directional energy changes;	May affect sources/sinks of littoral drift	Minor seabreeze effects
Onshore – Offshore	Changed distribution of motive energy; breaker depth; wave refracted angle	Minor effect	Dune recovery times	Wave directional energy changes; magnitude and duration of storms	May affect sources/sinks of littoral drift	Seabreeze effects
Aeolian	No effect	Minor effect	Major direct effect on dune mobility and direction	May affect quantity of available unconsolidated sand	Sand mobility	Seabreeze effects; vegetation
Deepwater	No effect	Direct effect on transport	No direct effect	Major effect on mobilisation	Minor effect	No effect
Estuaries	Mobilise tidal deltas, Scour/siltation of trained entrance	No direct effect	No direct effect	Local wind wave generation dependent on water depth	Minor impacts around drainage inlets	No effect
Hydraulics of Estuaries S11						
Tides	Reduced friction, increased tidal prism, increased heights and volumes	No effect	May influence tidal circulation patterns in some large shallow estuaries	May influence inlet characteristics	Changes in freshwater flows may influence tidal circulation	No effect
Wave Penetration	Increased wave penetration	Minor effect	Indirect effect	Wave directional energy changes; magnitude and duration of storms	Possible wave blocking changes	No effect
Seawater Penetration	Major effect on upstream penetration of saltwater	No effect	Indirect effect	No effect	Variable depending on freshwater flow events	No effect
Mixing	Increased exchange	No effect	Changed mixing characteristics	Changed mixing characteristics	Variable depending on freshwater flow events	No effect

Table 6: Relationships between key and secondary variables (continued).

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Quality of Coastal Waters S12						
Offshore	No effect	No effect	Minor effect	Changed mixing and turbidity	Minor effect	No effect
Nearshore	No effect	Minor effect	Changed mixing and turbidity	Changed mixing and turbidity	Changes in entrance turbidity	No effect
Estuarine	Altered depths, greater exchange; seawater penetration	Minor effect	Changed mixing and turbidity	Changed mixing and turbidity	Changes in salinity, stratification, turbidity	Minor effect on stratification and biological growth
Ecology S13	***Provided as a general guide only – seek specialist biological advice as necessary***					
Nekton and Plankton	No effect	Major effect on distribution	Changed mixing depths	Changed mixing depths	Localised salinity changes nearshore	No effect
Corals	Growth rates may not match sea level rise	Changed nutrient supply	Minor effect	Wave directional energy; magnitude and duration of storms	Localised salinity changes nearshore	Increased bleaching
Seagrasses	Shifting zonations; light penetration	Changed nutrient supply	Mixing and turbidity may affect light penetration	Wave directional energy; magnitude and duration of storms will favour rugged species	Localised salinity changes nearshore	Minor effect
Benthic	Shifting zonations; light penetration	Changed nutrient supply	Mixing and turbidity may affect light penetration	Wave directional energy; magnitude and duration of storms will favour rugged species	Localised salinity changes nearshore	No effect
Wetland	Species depth dependency effects	Changed nutrient supply	Minor effect	Minor effect	Changes in salinity profile may have major effect	Evapo-transpiration rates
Terrestrial	Waterlogged root systems; raised salinity; erosion/ inundation of shorelines	No effect	Minor effect	Minor effect	Growth rates especially via groundwater	Evapo-transpiration rates
Avifauna	Nesting areas may be affected	Changed food sources	Minor effect	Minor effect	Minor effect	Minor effect

For a high consequence of failure (low encounter probability) the appropriate design philosophy might be characterised by *robustness*. This aims to prevent "failure" of the facility by acknowledging the need for either a comfortable excess of design capacity (strength, displacement, resistance as appropriate) or the ability to subsequently adapt the design to suit changing climate change scenarios throughout its lifetime (enhancement, retrofitting, raising as appropriate).

Step 5: Select Appropriate Design Criteria

At this point it is necessary to identify the specific variables that may be affected by climate change. These will be evident from examination of the likely interactions between the primary and secondary variables in Table 5, as a function of the intended role and operation of the specific facility.

The design may then be prepared based on knowledge of existing climate conditions derived from the statistical analysis of measurements, hindcasting or simulation techniques as appropriate. Where insufficient knowledge exists relative to the assessed consequences of failure then additional studies should be undertaken to gain such knowledge. These additional studies should consider including the possible impact of existing climate trends, where appropriate.

The statistical description of the "failure" event will then normally involve an estimate of the likelihood of equalling or exceeding a given magnitude of that event. This is typically expressed as a function of the elapsed time of exposure to, or sampling of, the event process and requires selection of a design average recurrence interval (ARI or *return period*) and its associated threshold magnitude. Some designs may require further consideration of joint probability elements such as water level and wave height. Conveniently, the above considerations can be combined through the concept of the "encounter probability" R, which greatly assists the decision making process (Borgman, 1963).

The principal risk components of:

Threat:	Average Recurrence Interval or Return Period	T	y
Exposure:	Planning Horizon or Design Lifetime	N	y
Acceptability:	Risk of Encounter within that Lifetime	R	%

can be related by:

$$T = -\frac{N}{\ln[-{}^{R}\!/\!_{100}]} \tag{1}$$

This equation provides the appropriate average recurrence interval of the threat (T) to be considered in the design if, within the design life of N years, the *acceptable* risk of encounter (or possible failure at that level of threat) is chosen to be R. It is readily apparent from the summary of values presented below in Table 6, and shown graphically in Figure 9, that relatively high values of the average recurrence interval T will be required to limit the potential for failure of typical projects below a level of 10% over their lifetime. For example, if a structure is to have a 5% risk of encountering an event magnitude that is equalled or exceeded at least once during the next 50 years, then the design extreme event is one with a 975 year (say 1000 year) average recurrence interval. In fact, there is approximately a 64% chance of equalling *or exceeding* the 50 year recurrence interval magnitude in any consecutive period of 50 years. Expressed in another way, in the next 50 years there is a 5% chance that the 1000 year average recurrence level event *or greater* will occur, but a 64% chance that the 50 year event *or greater* will occur. More sophisticated analyses may also be undertaken to examine the probability of more than one instance of the design event occurring within the design life or even a specific number

… in the next 50 years there is a 5% chance that the 1000 year average recurrence level event or greater will occur …

occurring. The methods of Bea (1990), for example, also provide a useful analytical framework for structural reliability analysis.

Table 7: Design average recurrence interval *T*.

% Risk of Encounter (*R*)	**Design Life or Planning Horizon in Years (*N*)**				
	1	**10**	**20**	**50**	**100**
99	0.2	2.2	4.3	11	22
90	0.4	4.3	8.7	22	43
64	1.0	10	20	49	98
50	1.4	14	29	72	144
20	4.5	45	90	224	448
10	9.5	95	190	475	949
5	19	195	390	975	1950
1	99	995	1990	4975	9950

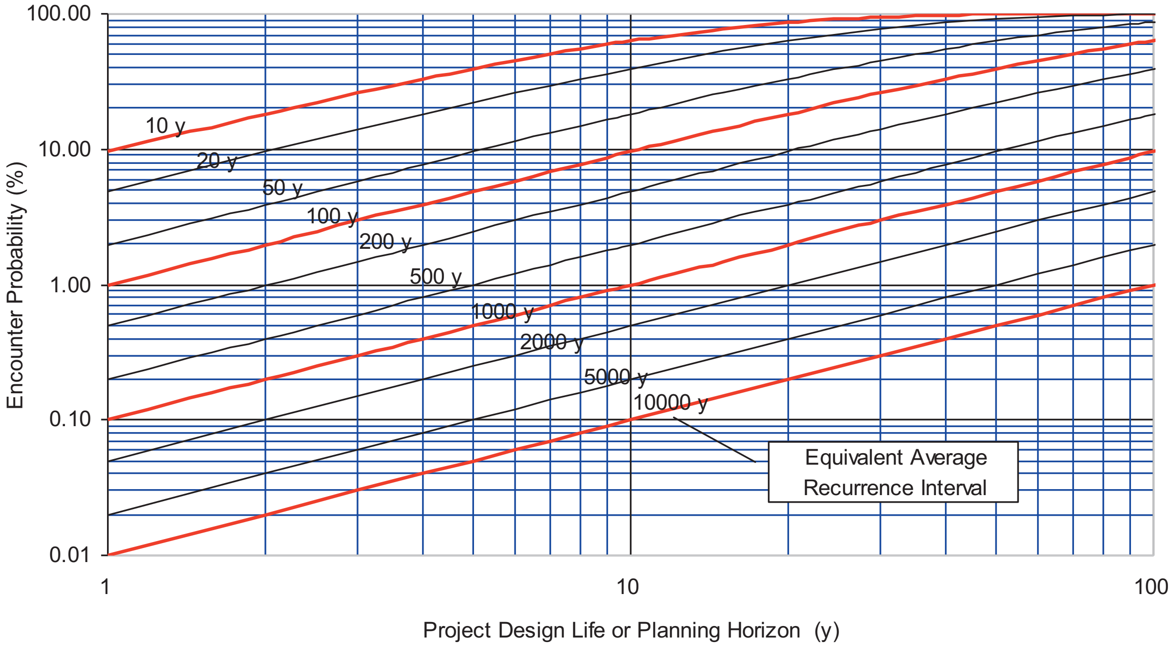

Figure 9: Relationship between encounter probability, design life and average recurrence interval.

While this method and its assumption of statistical stationarity has significant utility in allowing a rational consideration of risks, the changing climate condition will act to partly invalidate these assumptions over time. Accordingly, sensitivity testing is recommended as described below.

Step 6: Undertake a Sensitivity Analysis

Establishment of a *design interaction matrix* should facilitate this process, based on the current best estimates of climate change scenarios presently available or where no estimates are available, on an appropriate test assumption. In practical terms this might involve adjusting the modal value of a statistical distribution within certain bounds (simulating a bias or magnitude shift) or alternatively a change to the "slope" of the distribution (simulating a change in frequency of occurrence) or a combination of both effects. The degree of assumed change should reasonably relate to the published levels of possible climate change and consider "mean" and "upper" predictions. In many situations, rather than assuming a direct effect, it might be necessary to consider the "filtering" effects of a number of related processes, as for example embodied in Table 5. The statistical recombination of assumptions is preferred where possible to avoid unnecessary subjectivity at this stage of the assessment.

Appendix C provides a simple interaction matrix template that may assist in the preliminary assessment of climate change sensitivities to a particular design.

Step 7: Assess and Review Design Assumptions

Examine the outcome of the sensitivity analysis with respect to the implied consequences and assess the suitability of the final design.

Step 8: Adjust the Design if Necessary

Repeat assessment Steps 1 through 7 as appropriate to reassess design life, encounter probability or to increase robustness or adaptability to minimise future risk.

4.4 Example Assessments

The following detailed example impact assessments are provided for illustration of the method. The first case is of a complex offshore structure (fixed or floating), so as to illustrate the major aspects of the assessment methodology for a specific "engineered" facility. A second detailed example is provided in the next section for a nearshore tourism development where there is a greater reliance on "planned" facilities. Finally an example of a Greenfield coastal community is given.

4.4.1 Detailed Example 1: Fixed or Floating Offshore Structures

Design Life:

The typical application for such structures would be for oil or gas extraction and processing, although some may support transport or tourist facilities.

For oil and gas situations, the design life is likely to vary primarily as a function of the expected production life of the reservoir (5 to 20 years). Typically however, advances in product recovery technology (directional drilling etc.) and subsequent field exploration have caused the original design lives of many offshore facilities to be exceeded. Often costly retrofits have then become necessary to accommodate the additional weight of expanded processing facilities or stiffening to extend the fatigue and corrosion resistance of the major structural elements. Small reservoir situations with unmanned or subsea facilities may justify a design life of 10 years or less, depending on project economics. Larger developments would typically extend to 20 years and, where further project expansion is likely, up to 40 years or more.

Consequences of Failure:

For the majority of offshore situations, the consequences of failure both direct and indirect will be *very high*. Direct effects would involve possible loss of life, loss of production and income, reinstatement costs and contractual defaults and penalties. Indirect effects could be potential environmental damage (*e.g.* oil spill), compensation costs for clean-up, claims made for interruption in product supply and loss of employment or damage to regional economies.

Design Encounter Probability:

The discussion here is limited to considerations of environmental structural loading. Other design elements, such as risk of human error, mechanical breakdown, fire or explosion will significantly influence the overall design process for oil and gas processing facilities. The process, structural, geotechnical and ocean engineers should adopt consistent design encounter assumptions.

Where loss of life as a result of failure or major environmental impact is expected, a design event encounter probability range as low as 0.5% to 1% might be appropriate. This would require designing some crucial structural elements for environmental loadings with an average recurrence interval of between 2,000 and 10,000 years, depending on the chosen design life. Different encounter probabilities might be appropriate for other aspects of the design, e.g. loss of production might be tolerated at the 5% level or greater, depending on the cost and time to repair, contractual or labour issues etc.

Design Philosophy:

A robust design philosophy should be considered for offshore facilities. The design concepts of ultimate strength and reserve strength ratio would generally apply, as presented for example in Bea (1990).

Selection of Appropriate Design Criteria:

The necessary magnitude of the relevant criteria follows from the specification of design life and encounter probability, e.g. a 1% encounter in a 20 year life requires a 2,000 year average recurrence level magnitude. Where a single forcing element dictates the design, for example wind forcing, the design requirements might be satisfied by simply adopting the relevant (gust or mean) wind speed magnitude and direction (key variable K3) indicated by either data or, more likely, hindcast or simulated statistical analyses. However, for the normal offshore condition, extreme loadings do not occur in isolation but rather within complex storm events. The joint probability of environmental loading combinations will therefore often be an important consideration. In this case, the relative magnitude, phasing, dynamics and spatial variation over the structure of a number of environmental loadings (currents S2, winds S3, waves S4) becomes dominant. The structural response is then the sum total of these separate forcing functions combined often with dynamically variable resistance characteristics of the seabed (anchor attachment, pore pressures, pile skin friction etc.). The resulting statistical loading function(s) should then become the basis for the design rather than the separate independent incident (wind, wave or current) conditions.

Sensitivity Analysis of Climate Change Scenarios:

At this point an interaction matrix should be constructed to isolate those design elements most likely to be affected by climate change. A template is provided in **Appendix C,** which has been reduced here as Table 8 to include only those combinations relevant to the offshore example, using Table 6 for guidance:

Assess and Review Design Assumptions:

From Table 7, the principal impacts are seen to be local sea level, possible increased storminess with changes to local wind and wave climates (e.g. southern ocean, east coast low, monsoon, tropical cyclone) and perhaps some less critical operational matters.

Of these, sea level changes of the magnitudes presently predicted can and should be readily allowed for in a new design and at a relatively small overall cost. For existing structures, increased sea level will most noticeably cause inconvenience at tidal landings but this can be easily remedied. More importantly, a rising sea level decreases the underdeck wave clearance of fixed structures and may thereby significantly impact the encounter probability of failure. Retrofitting to increase structural strength or raise deck levels may then be a necessary option to maintain the original design risk of failure.

Increased storminess is potentially much more complex than sea level changes and the design allowance may need to be varied depending on the situation. For example, a location presently near the edge of tropical cyclone influence may experience a significant change in risk if the extent of cyclone influence increases. For a location already in a tropical cyclone region, the relative impact may be minor. These interpretations should be referred to specialist coastal and ocean engineers with appropriate numerical and statistical modelling capability to provide recommended design allowances.

4.4.2 Detailed Example 2: Nearshore Tourism Development

Design Life:

A typical design life of between 20 and 50 years might be adopted. This could depend upon the scale of the development, style of architecture, construction materials and overall economic plan. Given the harsh marine environment, maintenance costs might dictate a replacement cycle for some non-structural marine facilities and fittings of generally not more than 15 years, but this should not reduce the design capacity within the overall project design life.

Consequences of Failure:

This may have several dimensions. The first might relate to low probability storm-related damage to breakwaters, marinas, beaches, nearshore accommodation and infrastructure. This could result in possible loss of life, generally short term environmental damage and loss of income. The second dimension could relate to ongoing or operational matters such as beach and small craft amenity, wind and wave exposure, nearshore waters and groundwater quality, loss of desirable vegetation cover, potable water and the like. The major consequences of "failure" will likely be economic loss but environmental degradation could also occur and in some circumstances (e.g. storm surge) significant loss of life is possible without adequate warning or evacuation options.

Design Encounter Probability:

If loss of life is possible, for example such as an isolated low lying island or causeway situations, then relatively low design encounter probabilities are again advisable (akin to the preceding offshore design example). Where access to higher ground and shelter is readily available and warnings of severe conditions are likely, a higher encounter risk might be acceptable. Parts of the facility might be designed for differing levels of risk whereby high capital cost or protecting infrastructure such as breakwaters, causeways, hotels, central offices (administration, catering, commercial) are exposed to relatively low levels of risk over the life of the project. Bungalow-style accommodation units from which patrons would be evacuated and where damage could be readily repaired might accept a moderate risk level. Non-hazardous stormwater overflow, roadways, sacrificial boardwalks, landings and other minor structures could accept an even higher risk where the consequences are minimal and the reinstatement costs are low. The adopted encounter probability levels may also be subject to legislative control in some areas and practitioners are expected to acquaint themselves with relevant regulations. The coastal and ocean engineer should liaise closely with the architect, builder, civil, structural, mechanical and electrical design engineers to ensure that consistent risk philosophies are being adopted across the project development.

Design Philosophy:

For those aspects of the development essential to its ongoing operational viability and environmental health and safety, a robust design philosophy should be considered. This might affect the management of the beach amenity whereby adequate setback distances need to be specified to maintain a natural active beach buffer zone, restricted dune access and vegetation control. It might lead to the need for special design studies to optimise circulation within marinas, modelling of breakwater stability, checking groundwater characteristics etc.

For ancillary elements of the development a *least regrets* philosophy might be considered. This might apply to boat landings, boardwalks, stormwater outlets, navigation markers, dredged depths, bar stability etc. The expectation would be that any "failure" of these items would be unlikely to cause secondary damage.

Table 8: Example interaction matrix for an offshore structure.

Offshore Structure Example Assessment	Mean Sea Level K1	Ocean Currents & Temperature K2	Wind Climate K3	Wave Climate K4	Rainfall / Runoff K5	Air Temperature K6
Local Sea Level S1	– design for increases over lifetime in regard to tide and wave clearance – potential for minor changes in barometric surge heights	– some minor changes to seasonal mean levels possible due to density changes	– some minor changes to seasonal mean levels possible	– no effect	– no effect	– minor effect
Local Currents S2	– no effect	– likely seasonal changes which might affect operations -baroclinic currents may change	– possible major effect through increased storminess	– minor effect	– no effect	– no effect
Local Winds S3	– no effect	– minor effect	– possible major effect through increased storminess	– no effect	– no effect	– minor effect
Local Waves S4	– minor effect	– minor effect	– indirect effect	– possible major effect through increased storminess – possible changes in swell direction	– no effect	– no effect
Effects on Structures S5	– allowance must be incorporated	– minor effect	– potentially major effect on loadings	– potentially major effect on loadings, fatigue	– no effect	– minor operational or process changes
Sediment Transport S10	– no effect	– minor effect	– no effect	– possible incr eased scour around foundations, pipelines	– no effect	– no effect
Quality of Coastal Waters S12	– no effect	– possible changes in oil spill destinations and travel times	– possible changes in oil spill destinations and travel times	– minor mixing effects	– no effect	– minor effect
Ecology S13	– no effect	– minor effect	– minor effect	– minor effect	– no effect	– no effect

Selection of Appropriate Design Criteria:

The necessary magnitude of the relevant criteria follows from the specification of design life and encounter probability, e.g. a 5% encounter in a 50 year life requires a 1000 year average recurrence level magnitude design event. As in the example of the offshore structure, joint probability considerations will be important for the consideration of the occurrence of tropical cyclone storm surge, tide and wave setup on overland flooding, beach and breakwater stability. It can normally be assumed that wind and wave conditions will be closely correlated, *i.e.* those encountered conditions will have essentially the same average recurrence intervals. Specialist advice may be necessary on such matters if the development is found to be sensitive to the assumptions made during design.

Sensitivity Analysis of Climate Change Scenarios:

The interaction matrix in Table 9, highlights the likely major areas that should be examined for their sensitivity to the adopted design.

Assess and Review Design Assumptions:

The interaction matrix highlights sea level increases (K1), wind (K3) and wave (K4) climate changes as being the major concerns. These have impacts across a wide range of the secondary variables and the design philosophy would need to ensure that potential changes would have minimal effect on the development. This might require conservatism in critical design components such as breakwater design, harbour entrance, major buildings and setbacks etc.

4.4.3 Detailed Example 3: Greenfield Coastal Community

Design Life:

The design life of an entire community, comprising housing, commercial, industrial and infrastructure services may well be regarded as between 50 and 100 years. While commercial replacement might occur as frequently as 10 to 20 years, domestic housing of high quality may survive several generations before replacement, and be renovated periodically. Infrastructure is normally expected to function for at least 50 years and be gradually augmented, unless directly exposed to a harsh marine environment. In that case maintenance costs might dictate a replacement cycle for non-structural marine facilities and fittings of generally not more than 15 years.

The key element is the permitted change in land use. Current planning frameworks make downgrading of landuse extremely difficult. A decision to change land use (e.g. from rural to residential) has no design horizon and that use (or its expectation) then continues in perpetuity. One further aspect of such a community that complicates adaptation responses is that the land comprising the development is likely to be in the ownership of hundreds or even thousands of individuals. Coordinating replacement of housing and infrastructure in a strategic manner is likely to be a practical impossibility in these circumstances, leading to ad hoc, piecemeal responses to the range of hazards likely to have an impact on the community. Thus it might lead to longer term benefits if a higher priority is given to prevention of exposure to the hazards as the primary response, over expectations of future adaptation in such situations.

Consequences of Failure:

If there is direct marine exposure to some elements of the development then Example 2 effects will apply to those areas, such as low probability storm-related damage to breakwaters, marinas, beaches, nearshore facilities and exposed infrastructure. This could result in possible loss of life, generally short term environmental damage and loss of income. Further direct exposure might be through tidal creeks, drains and wetlands providing pathways for permanent inundation or increased frequency of flooding, either from the sea or as a result of increasing tailwater levels during terrestrial/fluvial flood events.

Table 9: Example interaction matrix for a nearshore tourism development.

Nearshore Tourism Development Example Assessment	**Mean Sea Level K1**	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Local Sea Level S1	– major effect in estuaries and tidal lakes – greater risk of storm surge inundation	– possible minor changes in seasonal variability of water level	– possible minor changes in seasonal variability of water level	– wave setup could increase	– possible flood interaction	– minor effect
Local Currents S2	– major direct effect in estuaries and tidal lakes	– possible changes to prevailing currents	– major direct effect	– possible major effect for barred entrances	– possible flood interaction	– no effect
Local Winds S3	– no effect	– minor effect	– major direct effect	– no effect	– no effect	– minor sea breeze effects
Local Waves S4	– major effect in shallow water regions	– minor effect	– indirect effect	– major direct effect	– minor effect	– no effect
Effects on Structures S5	– major direct effect	– minor effect	– major direct effect	– major direct effect	– major effect depending on location or purpose	– no effect
Groundwater S6	– major direct effect on quality and storage	– no effect	– no effect	– local setup may cause dynamic effects	– may affect phreatic surface	– minor effect
Coastal Flooding S7	– major direct effect on exposure, drainage, runoff	– no effect	– major direct effect via intensity and frequency of severe storms and cyclones	– major direct effect via wave setup at open sites	– direct effect via changes in rainfall distribution, intensity and frequency	– no effect
Beach Response S8	– major effect of recession with sea level rise – realignment	– minor effect	– possible changes to aeolian transport processes	– major effects of wave directional energy changes	– possible effects of estuary discharges	– possible vegetation changes; sea breeze effects
Foreshore Stability S9	– major changes to wave penetration possible -groundwater levels – sediments exposed to erosion	– minor effect	– dune shape and vegetation	– major direct effects on scarp toe erosion – runup and overtopping – breakthrough	– elevated phreatic levels; pore pressure changes; vegetation	– vegetation changes; weathering

Nearshore Tourism Development Example Assessment	**Mean Sea Level K1**	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Sediment Transport S10	– changed distribution of motive energy; breaker depth; wave refracted angle	– may affect sediment supply	– longshore wind generated currents – effect on dune mobility and direction	– wave directional energy changes; magnitude and duration of storms	– may affect sources/ sinks of littoral drift	– seabreeze effects; vegetation
Hydraulics of Estuaries S11	– major impact on tidal prism, seawater intrusion	– minor effect	– influence on circulation in shallow waters	– effect on inlet characteristics, mixing	– major changes could influence tidal circulation, density	– no effect
Quality of Coastal Waters S12	– major effect on exchange rates in estuaries	– minor effect	– possible changes in mixing and turbidity	– possible changes in mixing and turbidity	– possible changes in salinity, stratification, turbidity	– minor effect
Ecology S13	– major changes in zonation	– possible nutrient changes	– possible changes in mixing and turbidity	– major changes in zonation	– localised salinity changes	– possible effects coral reefs and foreshore vegetation

For all non-direct exposure, the intention should be to limit development so as to avoid hazard exposure or limit failure within the design life. For this purpose, planning zones with differing design lives might be appropriate, anticipating adoption of a “planned retreat” predicated on identified hazard triggers, such as erosion incursion or a predetermined hazard level (say 50 y ARI etc.). Subject to legal frameworks and agreements, affected lands could be either converted to open space or re-developed under additional conditions. It is not possible in these guidelines to assess the practical risks and community costs associated with retreat or abandonment of large numbers of titles under individual ownership.

Design Encounter Probability:

Where loss of life is possible, for example such as isolated low lying land or causeway situations, then relatively low design encounter probabilities are advisable. Where access (evacuation routes) to higher ground and shelter is readily available and warnings of severe conditions are likely, a higher encounter risk might be acceptable. Parts of the community might be designed for differing levels of risk whereby high capital cost or protecting infrastructure such as breakwaters, groynes, seawalls, causeways, bridges are exposed to relatively low levels of risk over the life of the community.

Commercial and industrial developments can often be preferentially located in predominantly flat areas with a higher risk (but still acceptable) of flooding, whereby car parks and undercrofts can be used as floodways or flood storage, but floor levels are suspended to meet a low operational risk level.

Public space should be utilised and set aside for temporary flood conveyance at moderate levels of risk. Non-hazardous stormwater overflow, roadways, sacrificial boardwalks, landings and other minor structures could also accept a moderate risk where the consequences are minimal and the reinstatement costs are low.

Public housing and public buildings should never be sited where exposed to ocean impacts, whether via direct surge, tide, setup and runup events or erosion encroachment. Low velocity flooding could be tolerated with moderate risk if floor levels are suspended to meet a very low level of risk.

Emergency infrastructure (police, ambulance, hospital, fire and rescue, control and command, communication hubs, shelters, aged care facilities, schools etc.) must be located in areas with very low risk of impact and with appropriate storm accessible transport corridors.

The adopted encounter probability levels and relevant climate change parameters to be used may also be subject to legislative control in some areas and practitioners are expected to acquaint themselves with relevant regulations. The coastal and ocean engineer should liaise closely with the architect, builder, civil, structural, mechanical and electrical design engineers to ensure that consistent risk philosophies are being adopted across the project development.

Design Philosophy:

For those aspects of the community essential to its economic viability and environmental health and safety, a robust design philosophy should be considered, supported by detailed investigation and design (breakwaters, bridges, floodways, groundwater). Sea level rise issues should be addressed through planning to maintain a natural active beach buffer zone over the design life, suitably elevated building sites and/or ensure adequate freeboard for low velocity flooding events. Alienation of some coastal lands may be an option in specific situations for environmental and/or hazard considerations. Fortification of residential or commercial premises as a long term planning strategy should be avoided.

Underground carparks that are at a finite risk of flooding should be subject to closure and inspection procedures and include safe emergency egress.

For ancillary elements of the community a *least regrets* philosophy might be considered. This might apply to minor recreational or sporting structures, boat landings, boardwalks, stormwater outlets, etc. The expectation would be that any "failure" of these items would be unlikely to cause secondary damage or dangers.

Selection of Appropriate Design Criteria:

The necessary magnitude of the relevant criteria follows from the specification of design life and encounter probability, e.g. a 5% encounter in a 50 year life requires a 1000 year average recurrence level magnitude design event. As with the other examples, joint probability considerations may be important for the consideration of the occurrence of storm surge, tide and wave setup on overland flooding, beach and breakwater stability.

It can normally be assumed that wind and wave conditions will be closely correlated, i.e. those encountered conditions will have essentially the same average recurrence intervals. Riverine flooding in situations of short stream concentration times may also require allowance for raised surge-affected tailwater levels. Specialist advice may be necessary on such matters if the development is found to be sensitive to the assumptions made during design.

Sensitivity Analysis of Climate Change Scenarios:

The interaction matrix in Table 9 is deemed equally applicable to this example and highlights the likely major areas that should be examined for their sensitivity to the adopted design.

Assess and Review Design Assumptions:

The interaction matrix highlights sea level increases (K1), wind (K3) and wave (K4) climate changes as being the major concerns. These have impacts across a wide range of the secondary variables and the design philosophy would need to ensure that potential changes would have minimal effect on the community. For Greenfield sites, sensitivity analyses concentrating on upper bound estimates for climate change should be carefully considered.

4.5 Summary

The interaction matrix method is recommended here as an objective approach for considering the possible impacts of climate change in coastal and ocean engineering practice. Ideally, such an assessment should be a group process involving not just the relevant technical personnel but a broad group of interests and stakeholders. In 1991, this technique was developed from a series of workshops hosted by the NCCOE that involved a collective assessment from more than 20 practising coastal and ocean engineers, who worked through a range of typical projects (refer Appendix A). Practitioners are therefore urged to incorporate peer review into their quality assurance procedures wherever possible to ensure a critical and objective consideration of the possible impacts of climate change.

5. RESEARCH AND MONITORING NEEDS

5.1 The Scientific Basis

The following is presented as a commentary on the present status of research and monitoring needs for increasing the understanding of potential climate change and its impacts on the coastal and ocean environment.

An extensive research effort is directed towards projecting the degree and timing of possible climate change. This primarily centres on the complex numerical modelling of the climate on a global scale, where the Earth itself becomes the control volume. This facilitates the use of aggregated data from a number of sites around the world, an averaging of trends to provide a reference point and then the calibration of models against the observed historical changes. Numerical model physics continues to be developed, with the representation of ocean-atmosphere coupling becoming more sophisticated. Modelling at smaller scales is considered to be less reliable because it stretches the validity of the numerical model assumptions, forces consideration of finer sub-resolution scale interactions and suffers from a lack of data at the regional scale.

All of the above research is directed towards more reliable predictions of the state of future climate. It takes place within essentially a competitive academic framework and is funded primarily by Government. Continuing work that focuses on demonstrating improved modelling accuracy with clear regional application is to be encouraged and supported.

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5.2 Impacts, Adaptation and Vulnerability to Climate Change

Quantifying the subsequent impacts of possible climate change and the environmental adaptations that might occur are much more complex than determining the overall state of climate from a global control volume perspective. This is primarily related to the already limited state of knowledge of the many complex interacting temporal and spatial scales of oceanic, terrestrial and atmospheric processes. Each of these elements is already subject to extensive but specific numerical modelling efforts in the quest to understand present system behaviour. To argue that such models of present system behaviour would perform with the same skill level when addressing climate change remains a moot point. While climate change research in these areas is still essential, a focus on understanding observed processes is imperative in the short term, avoiding the temptation of making premature or weakly founded predictions that may simply serve to add to the confusion of knowledge.

The possible biological impacts and adaptations to the changing physical environment remain an essential consideration. While many studies exist that are scenario driven, more baseline experimentation and study appears highly desirable.

Societal adaptation and mitigation strategies ultimately will need to operate at the regional and local scale. It is therefore much more difficult to treat this aspect of the problem in an objective scientific or mathematical way. While some of the more obvious climate impacts and possible solutions have already been extensively canvassed, it is likely that more subtle changes may ultimately cause the most severe impacts in certain regions. The relative importance of potential sea level rise versus changing wave energy flux is a case in point. These aspects can be addressed by an intelligent planning regimen but need to be supported by scientifically based hazard assessments to provide the parameters and limits for planning. Much exists in the literature on the planning process and a further decade of discussion will likely add little to this knowledge. *Action* is needed to establish the legislative frameworks and to provide the essential scientific parameters for the planning authorities such as safe setbacks, sea level limits, bunded zones, infrastructure replacement and aquifer management plans etc. Effective legislative action requires strong political will, while the identification of the threats and treatment options requires the harnessing of appropriate engineering and related scientific expertise and provision of research and investigation funding.

5.3 Coastal and Ocean Engineering Issues

Engineering, whether by investigation or actual works, is a major vehicle for physical intervention in the coastal/ocean zone. Coastal and ocean engineering investigation and research are most vital, yet to-date, essentially non-funded component of the response to climate change in Australia. The engineering perspective is clearly essential for addressing the feasibility of adopting specific mitigation options and the subsequent selection of practical planning parameters. Engineering assessment requires upstream inputs from the atmospheric and oceanographic sciences but then applies that knowledge to the risk assessment of those climate impacts on the natural (to keep it that way) and the built (to maintain it) coastal and ocean environment.

Climate change is but one of many pertinent issues that have been previously identified by the NCCOE (NCCOE, 1991; 1993; 1995; 2004a; 2004b) as requiring a concerted engineering research effort and which need to be underpinned by long-term strategic data collection programs.

The numerical prediction of potential coastal and ocean zone impacts will remain unverified and of limited practical application without significant (i.e. 50 or more years) accumulated high resolution regional data on:

- sea level variation
- shoreline changes
- estuary dynamics
- aquifer responses
- nearshore and offshore wind, wave and current characteristics
- sediment transport mechanisms.

Without significant accumulated data … numerical prediction of potential coastal and ocean zone impacts will remain unverified and of limited practical application.

The following are therefore seen as the more significant issues affecting progress on climate change impacts of relevance to coastal and ocean engineering issues:

A lack of relevant coastal and ocean data sets

While some long term wind (e.g. Bureau of Meteorology; 60 year) and wave datasets (e.g. NSW and Qld governments; 35 year) exist and are of immense value, much collected data around Australia is sparse, incomplete, random and unintegrated. Urgent action is required to establish or expand engineering-related coastal and ocean data collection programs across Australia. To achieve this, the increasing trend of reduction in funding for public engineering and infrastructure projects, and the loss of government engineering expertise in decision making, must be reversed. Monies may need to be allocated for the acquisition of long term physical data sets that can be used for verified studies in the future.

Verifiable regional climate predictions

This requires the continuation of ongoing core research by climate specialists (atmospheric scientists, meteorologists and oceanographers) leading to model development and sensitivity testing against historical data sets. Verification of climate trends, however, will necessarily await the accumulation of relevant data.

Engineering-based impacts and mitigation research

It has been estimated (NCCOE, 2004) that less than 10% of Australia's climate change research budget is directed at coastal and ocean related issues and impacts, with most of that amount allocated to sea level monitoring alone. Of this, only a very small fraction has been undertaken by *engineering* research organisations. Concerted efforts need to be made by Engineers Australia and individual engineering research organisations to gain greater access to the available pool of research funds and to influence the priorities for allocation of funds.

NCCOE (1995), for example, recommended a national program be undertaken to assess the coastal impacts of climate change using a *quantitative risk management* approach that could form the basis of long term planning and management strategies. This was expected to be a major undertaking conducted over many years and taking some time to plan and develop the appropriate methodology. Much of the necessary expertise, numerical tools and actual experience for undertaking such studies already exists within the coastal and ocean engineering fraternity in Australia. These studies would ideally be multi-disciplinary, calling on additional advice from scientists (earth, ocean, climate, biological) and coastal planners and managers (environment, tourism, recreation, transport, ports) as required.

Less than 10% of Australia's climate change research budget is directed at coastal and ocean related issues and impacts …

In recent years, additional national funding for natural hazards risk assessment and mitigation at the Local Government level has become available through the Commonwealth Government, often administered by, and with contributions from, State governments. Some jurisdictions have undertaken significant data collection and risk assessment projects, but without nationally consistent methodologies and standards. This highlights that there has been no framework put in place to ensure the effectiveness and consistency of the studies and most of these initiatives represent a minor investment compared with what is needed to underpin the long term planning and sustainability of coastal communities. The quantum of funding typically being allocated continues to be well below the median market price of a single dwelling in any of the affected areas. This limits the accuracy, comprehensiveness and detail of such studies to a level far short of what is possible with current knowledge and tools.

6. GLOSSARY

AOGCM	Atmosphere-Ocean Global Climate Model
ACE CRC	Antarctic Climate and Ecosystems CRC (UTAS/CSIRO)
ARI	Average Recurrence Interval or Return Period
AR4	IPCC Assessment Report 4
BoM	Bureau of Meteorology
CAWCR	Centre for Australian Weather and Climate Research (BoM/CSIRO)
CFC	Chloroflourocarbons (refrigerant gases)
CMAR	CSIRO Division of Marine and Atmospheric Research
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEE	Australian Government Department of Climate Change and Energy Efficiency
EA	Engineers Australia
ENSO	El Niño – Southern Oscillation
FAR	IPCC First Assessment Report
HCFC	Hydrochloroflourocarbons (refrigerant gases)
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Change
MPI	Maximum Potential Intensity of tropical cyclones
NCCOE	National Committee on Coastal and Ocean Engineering
NTC	National Tidal Centre
SAR	IPCC Second Assessment Report
SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperature
TAR	Third Assessment Report of the IPCC
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
UVB	Ultra-Violet B solar radiation.
WMO	World Meteorological Organization (part of the United Nations)

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PSMSL, Permanent Service for Mean Sea Level. http://www.pol.ac.uk/psmsl/

SERM2, Simple Estuarine Response Model II. The SERM II project is an extension of the Simple Estuarine Response Model (SERM), developed as part of the National Land and Water Resource Audit (NLWRA). http://www.per.marine.csiro.au/serm2/

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APPENDIX A – BASIS OF THE NCCOE METHODOLOGY FOR ASSESSMENT OF CLIMATE CHANGE IMPLICATIONS

In 1990, concerned with the growing proliferation of differing approaches being taken by government agencies, local councils and consultants to cater for climate change effects, the National Committee on Coastal and Ocean Engineering (NCCOE) decided to take a leadership role. With supporting funding provided under the Commonwealth Local Government Development Program, the NCCOE moved to develop a recognised set of guidelines for coastal engineers to responsibly consider the methods of dealing with the potential for climate change.

It was seen as essential that a broad spectrum of engineers from academia, all levels of government and consulting organisations be involved so that it would be clear to the profession and others that the guidelines represented a "state of the art" statement by the Institution of Engineers, Australia, in regard to the practice of coastal and ocean engineering. Accordingly an open workshop process was developed that drew upon the requisite range of peer knowledge and experience from more than 20 professional engineers at that time. When the outcomes from that process were published (NCCOE, 1991) it was one of the first profession-wide successes in developing a considered methodology to address enhanced Greenhouse issues in Australia.

The present update represents an expansion of the original document made in response to requests from the coastal and ocean engineering profession in Australia. It fulfils a need to reflect the most recent climate change scenarios, and is designed to complement the coastal engineering guidelines for ecologically sustainable development (NCCOE, 2004). The original assessment methodology concepts developed by peer consensus in 1990 have been retained and it is anticipated that future workshop updates will be held as the need arises to review the basic methodology.

APPENDIX B – INTENDED AUDIENCE AND SCOPE OF APPLICATION

This document is designed primarily for use by professional engineers with expertise in and responsibility for works and facilities within the coastal and ocean field. It is expected that such engineers would be those able to satisfy the following definition of a coastal and ocean engineer and possess the level of qualifications and experience set out below.

Definition

Coastal and ocean engineering is a specialised branch of civil engineering that deals with the investigation, design, construction and maintenance of coastal and ocean related projects or facilities and the provision of technical advice for planning and management of natural processes in the near-shore and ocean zones. The coastal and ocean engineer must ensure that facilities in these regions allow for the influence of prevailing winds, waves, tides, currents and sediment movements, optimise the consequent adverse and beneficial environmental effects and minimise risks to life and property. These aims must be achieved for the operational and design conditions and for both the construction and post operational phases of any project. In addition to understanding the geomorphological and ecological development of the marine environment, the coastal and ocean engineer is required to make quantitative assessments and predictions of the physical characteristics of the environment in so far as it impacts human needs. These assessments depend upon the availability of reliable physical data sets over a range of space and time scales, sophisticated statistical techniques and often the use of complex numerical models of the dynamic interfaces between atmosphere, land and sea.

Coastal and Ocean Engineering Qualifications

A qualified Coastal and Ocean Engineer is expected to give due consideration to all the natural processes involved and to be responsible for the consequence of human intervention in the near-shore zone to ensure ecologically sustainable development. It is recommended that for a person to be considered suitably qualified, he or she should meet the following essential minimum requirements:

- A tertiary qualification in Engineering with particular relevance to coastal and ocean engineering.
- Membership (MIEAust) of Engineers Australia (EA).
- Chartered Professional Engineer (CPEng), registered on NPER.
- Membership of the Civil College of Engineers Australia.
- State registration where applicable, e.g. RPEQ.
- Experience in development of coast protection strategy or investigation, design and construction of coastal and ocean works.
- Experience in environmental assessment with particular emphasis on coastal and ocean engineering.
- Knowledge of the processes and methods involved in coastal and ocean engineering.

In addition to the above, further desirable requirements include:

- Post-graduate qualifications and/or studies in coastal and ocean engineering or related fields.
- Experience and knowledge in the earth sciences relevant to coastal management.

Recognised areas of further speciality and experience may include:

- ports and harbours, dredging and reclamation
- breakwaters, seawalls and revetments
- sediment transport, beach nourishment
- coastal management and planning
- coral reefs and islands
- hydraulics of estuaries, rivers and canals
- water quality, mixing and dispersion
- physical hydraulic scale modelling
- numerical modelling of tides, currents, waves and storm surge
- data collection and analysis
- natural hazards risk assessment
- vessel motion analysis
- marine pipelines and offshore structures
- design criteria assessment
- meteorology, oceanography, statistics.

APPENDIX C – IMPACT ASSESSMENT INTERACTION MATRIX TEMPLATE

This template may be useful for the preliminary assessment of the major interactions between the key climate change variables (K1 to K6) and the secondary or process variables (S1 to S13) in accordance with the recommended procedures of Section 4 and the interactions from Table 6.

	Mean Sea Level K1	**Ocean Currents & Temperature K2**	**Wind Climate K3**	**Wave Climate K4**	**Rainfall / Runoff K5**	**Air Temperature K6**
Local Sea Level S1						
Local Currents S2						
Local Winds S3						
Local Waves S4						
Effects on Structures S5						
Groundwater S6						
Coastal Flooding S7						
Beach Response S8						
Foreshore Stability S9						
Sediment Transport S10						
Hydraulics of Estuaries S11						
Quality of Coastal Waters S12						
Ecology S13						