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ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

BRIEFING:

a post-IPCC AR4 update on sea-level rise

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1. executive summary

In this briefing, we address the science of sea-level rise and briefly mention the potential impacts of sea-level rise. We report recent progress in understanding sea-level rise and also clarify confusion around interpretations of the IPCC sea-level projections.

Rising sea levels are a major impact of climate change and are likely to impact many millions of people by the year 2100.

While sea level has varied by more than 120 m during ice age cycles, there was little net change in global average sea level from 0 AD until about 1800 AD – the time during which most of the world's coastal development has occurred. Over the last 130 years, the rate of sea-level rise has increased and since the launch of satellites to measure sea levels in the early 1990s, it is over 3 mm/year. This rate is unprecedented in the 20th century.

Importantly, sea-level projections for the 21st century from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) of 2001 and the Fourth Assessment Report (AR4) of 2007 are similar when the qualifying statements in the AR4 are considered.

There have also been some significant developments since the AR4 report was released.

Observed sea level is currently tracking near the upper limit of the IPCC projections from the start date of the projections in 1990.

There is increasing concern about the potential instability of both the Greenland and the West Antarctic Ice Sheets leading to a more rapid rate of sea-level rise than the current model projections. While our understanding of the relevant processes is limited, it is important to recognize that the uncertainties are essentially one-sided: the processes can only lead to a *higher* rate of sea-level rise than current model projections.

Without significant and urgent mitigation of greenhouse gas emissions, the long-term survival of the Greenland Ice Sheet is at risk. While surface melting alone would take many centuries to contribute metres to sea-level rise, any continuing or accelerated glacial outflow would lead to a more rapid contribution to sea-level rise.

Some areas of the Australian coastline are potentially exposed to serious impacts from sea-level rise and extreme events. Observations confirm that sea level is rising around Australia, increasing the frequency of extreme sea-level events of a given magnitude. For many locations, sea-level rise means that the present one-in-a-hundred-year event could potentially occur more than once a year by 2100.

Sea-level rise will continue for at least a thousand years after greenhouse gas concentrations are stabilised. Impacts will be felt through both changes in mean sea level and also by increases in the frequency and intensity of extreme events.

An early warning of any further acceleration in the rate of sea-level rise would underpin future mitigation and adaptation decisions.

To address sea-level rise and its impacts requires partnerships between science, government, business and community sectors. These partnerships are required now and will need to be strengthened during the 21st century.

Photo: John Hunter

2. introduction

Sea-level rise is a major impact of climate change. Globally, at least tens of millions of people living within the coastal zone may have to respond to coastal flooding events by the end of the 21st century.

Many of the world's major cities are built in low-lying coastal regions. Impacts of sea-level rise include inundation of coastal areas, coastal erosion, saltwater intrusion into aquifers, loss of coastal wetlands and mangrove areas, and impacts on biodiversity.

Sea-level projections reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4)[1] of 2007 have been unnecessarily controversial.

At one extreme, a number of public reports have focused on the headline numbers in the table of the sea-level projections, ignoring the additional statements about ice sheets. These have been reported by some as a reduction in the sea-level projections since the IPCC Third Assessment Report (TAR)[2] of 2001.

This reported decrease in the projections is in conflict with observations published in reputable peer-reviewed journals by a number of leading glaciologists. They argue that we are already seeing worrying indications of instabilities in both the Greenland and West Antarctic Ice Sheets that could lead to a substantially larger rate of sea-level rise than the 2007 projections. In addition, some scientists have expressed concern that the IPCC did not sufficiently highlight the possibility of larger rates of rise than the headline figures for sea-level rise and the potential risk from a major ice-sheet contribution to sea-level rise.

At the other extreme, some media statements indicate that a sea-level rise of many metres during the 21st century is likely unless immediate and drastic mitigation of greenhouse gas emissions are implemented. Current scientific estimates do not support contentions of many metres of sea-level rise during this century, although such values might apply over several centuries.

Photo: John Hunter

3. the ipcc findings

Major sea-level rise findings reported in the AR4 (and TAR)

The TAR[2] included a chapter focused specifically on sea-level rise, but there was no specific sea-level rise chapter in the AR4.[1]

Instead, sea-level related issues were discussed in several chapters of the report. While this structure allowed experts to consider individual aspects of sea-level rise, there was no dedicated synthesis of all the contributing factors. Most of the final synthesis was therefore confined to the Technical Summary and the Summary for Policy Makers.

The major findings were:

Sea level has changed dramatically in the past

- At the time of the last interglacial period, about 125,000 years ago, sea level was likely 4–6 m higher than it was during the 20th century, at *polar* average temperatures 3°C to 5°C higher than present values. Loss of ice from the Greenland Ice Sheet was likely to have contributed no more than 4 m to this higher sea level and there may also have been a contribution from the Antarctic Ice Sheet.
- Sea level was 120 m or more below present day values at the last glacial maximum about 21,000 years ago. The TAR reported that during the disintegration of the northern hemisphere ice sheets at the end of the last glacial maximum, sea level rose at an average rate of 1 m/century, with peak rates of about 4 m/century.
- Over the last 2,000 years, when many of our coastal cities became established, sea-level rise was less than 0.2 mm/year on average.

The rate of sea-level rise has increased

- The rate of sea-level rise increased from the 19th to the 20th century when it reached an average rate of about 1.7 mm/year (Figure 1).
- The average rate of sea-level rise from 1961 to 2003 was 1.8 mm/year and increased to 3.1 mm/year from 1993 to 2003. Whether this latter rate indicates decadal variability or an increase in the long-term trend will only become clear when longer observational records are available.

Ocean thermal expansion and melting of non-polar glaciers and ice caps are the largest contributions to recent sea-level rise

- Observations since 1961 show that the oceans have warmed as the result of absorbing more than 80% of the heat added to the climate system largely because of the enhanced greenhouse effect. The warming has caused the oceans to expand, contributing to sea-level rise.
- Observations since 1961 show that widespread decreases in glaciers and ice caps (excluding the Greenland and Antarctic Ice Sheets) have contributed significantly to sea-level rise. These areas are estimated to contain only enough water to raise global average sea level by less than about 40 cm.
- From 1993 to 2003, both the Greenland and Antarctic Ice Sheets are thought to have contributed to sea-level rise. The flow speeds of some of the outlet glaciers draining ice from the Greenland and Antarctic interiors have increased, often following the loss or reduction of ice shelves around the ice sheet margins.

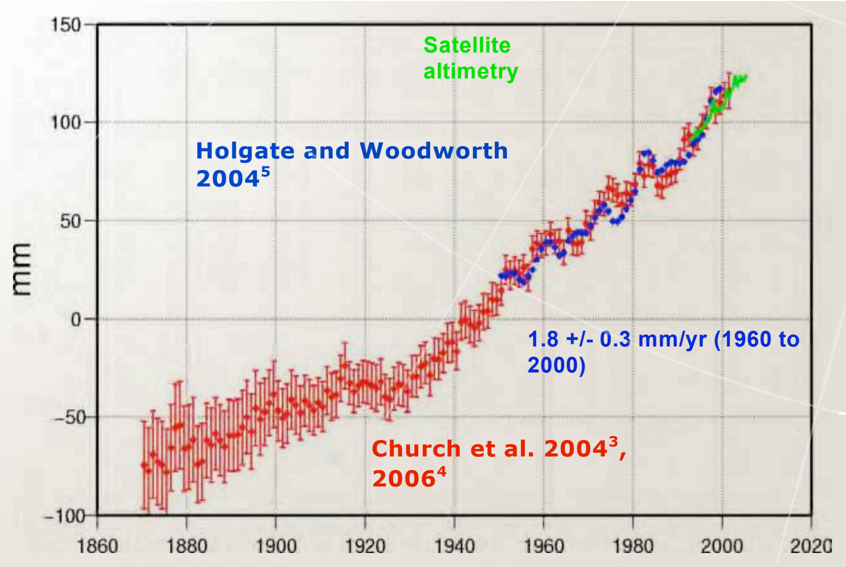

Figure 1.
Estimates of 20th century global averaged sea level.[1]

Two estimates of global averaged sea level from coastal sea-level data are shown by the red (with error estimates) and blue curves. The green curve shows global averaged sea level measured by satellite from 1993 to 2003.

The contribution of the Greenland and Antarctic Ice Sheets over recent decades was estimated to be less than 20% of the observed sea-level rise. However, the prospect of faster loss of ice through persistent, possibly accelerating, sliding of the ice sheets and outlet glaciers over the bedrock (called a 'dynamic' response) is a new and important finding signaled in the AR4.

Total melting of the Greenland Ice Sheet would increase sea level by about 7 m. Total melting of the Antarctic Ice Sheet would increase sea level by about 60 m, of which around 6 m would come from the West Antarctic Ice Sheet and the remainder from the East Antarctic Ice Sheet. The Greenland and West Antarctic Ice Sheets are those believed to be most vulnerable to dynamic ice loss due to climate change.

The TAR and the AR4 Projections of future sea-level rise are similar

The projections of sea-level rise for the 21st century are shown in Figure 2.

For the TAR, the projections are for 2100 compared with 1990 levels. For the AR4, the projections are for the 2090 to 2100 decade (shown as the bars plotted at 2095) compared with 1980 to 2000 averages (approximately equal to the 1990 values).

- The average of the TAR model projections for the full range of greenhouse gas scenarios are about 30–50 cm (dark shading in Figure 2). The range of all model projections over all scenarios is about 20–70 cm (light shading). The full range of projections, including an allowance for uncertainty in estimates of contributions from land-based ice, were for a sea-level rise of 9–88 cm (outer black lines).
- The AR4 model projections (with a 90% confidence range) are for a sea-level rise of 18–59 cm in 2095 (the magenta bar) plus an allowance of another 10–20 cm for a potential dynamic response of the ice sheets (the red bar).

Although this addition is never done explicitly in the AR4, the total projected range in sea-level rise would be 18–79 cm, once the allowance for dynamic ice sheet contributions is included. The AR4 specifically states: "Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise."

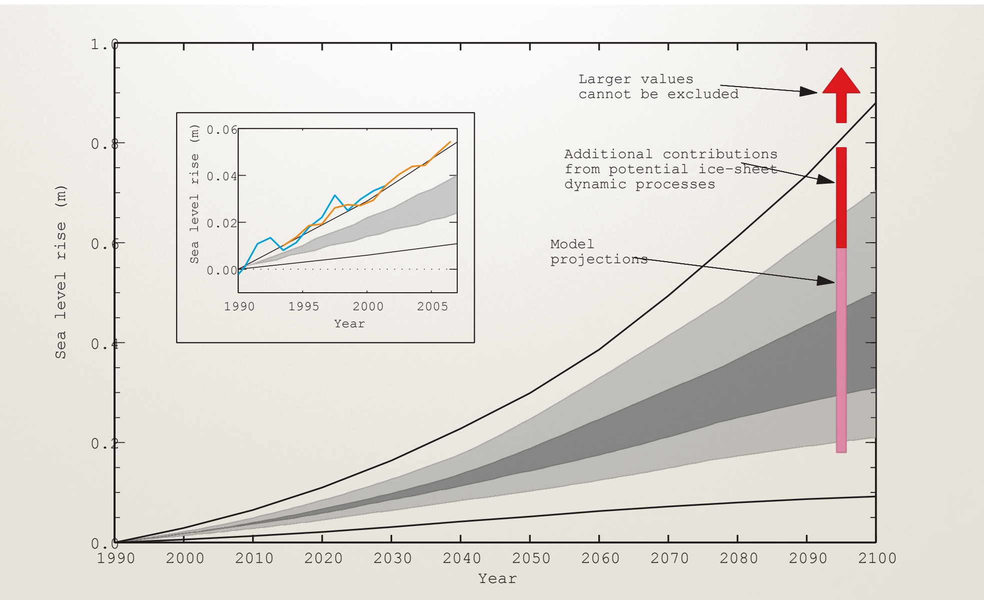

Figure 2. TAR and AR4 projections of sea-level rise.[2,7]

The TAR projections are indicated by the shaded regions and the curved lines are the upper and lower limits. The AR4 projections are the bars plotted at 2095. The inset shows sea level observed with satellite altimeters from 1993 to 2006 (orange) and observed with coastal sea-level measurements from 1990 to 2001 (blue).

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3. the ipcc findings

- The AR4 model projections (the magenta bar) approximately overlap with the equivalent TAR values (light shading). Also, after allowing for the potential dynamic response of 10–20 cm, the upper end of the AR4 and the TAR projections are approximately equivalent in 2095. That is, the upper limits of the two projections are similar.

The ice sheets may contribute significantly to future sea-level rise

- Surface melt of the Greenland Ice Sheet has increased and is projected to increase more rapidly than precipitation as temperatures increase. If global average temperature increases above some threshold, surface melting *alone* is projected to exceed precipitation, leading to an ongoing contraction of the ice sheet. This threshold is estimated as 3.1°C above pre-industrial values (with 95% confidence range from 1.9–5.1°C). Warming could exceed this value during the 21st century without effective mitigation of emissions. If these temperatures were maintained, they would lead to a virtually complete elimination of the Greenland Ice Sheet and a contribution to sea level of up to about 7 m over thousands of years from surface melting alone.
- Some recent observations suggest a rapid dynamic response of the Greenland and West Antarctic Ice Sheets, which could result in an accelerating contribution to sea-level rise. This has been included in an ad-hoc fashion in the projections.

  For the Greenland Ice Sheet, proposed mechanisms of the response include: surface melt water making its way to the base of the ice sheet, lubricating its motion and allowing the ice to slide more rapidly into the ocean; and the decay of ice shelves and the loss of their 'buttressing' effect on the seaward movement of the outlet glaciers.

  In Antarctica, the West Antarctic Ice Sheet is grounded below sea level, which allows warmer ocean water to melt the base of the ice sheet. This could potentially lead to significant instability of the ice sheet, particularly if the 'buttressing' effect of the seaward ice shelf was lost.

  Our understanding of these processes is limited. As a result, they are not included in current ice sheet models and there is no consensus as to how quickly they could cause sea level to rise. Note that these uncertainties are essentially one sided. That is, they could lead to a substantially more rapid rate of sea-level rise but they could not lead to a significantly slower rate of sea-level rise.
- Current projections suggest that the East Antarctic Ice Sheet will remain too cold for widespread surface melting and it is expected to gain mass from increased snowfall over the higher central regions. Net loss of mass could occur if a more rapid ice discharge into the sea around East Antarctica exceeds the rate of accumulation from snowfall over the interior.

Sea-level rise will continue

- Both past and future greenhouse gas emissions will contribute to sea-level rise for centuries to thousands of years because of the long lag-times involved in warming of the oceans and the response of ice sheets.

Photo: John Hunter

4. developments since the AR4 release

A number of recent developments are not included in the AR4 Assessment.

Sea level has been rising at close to the upper end of the IPCC projections

- Sea level observed with satellite altimeters from 1993 to 2006 and estimated from coastal sea-level measurements from 1990 to 2001 are tracking close to the upper limit of the TAR projections of 2001[7], which included an allowance for land–ice uncertainties. Recent altimeter measurements[6] indicate sea level is continuing to rise near the upper limit of the projections.
- Recognising the inadequacies of the current understanding of sea-level rise, simple statistical models relating observed sea levels to observed temperatures have been developed and applied with projected temperature increases to project future sea levels (Figure 3).[8, 9, 10] These have generally resulted in higher sea level projections for 2100, of up to 1.4 m.
- There are suggestions that the glacier and ice cap contributions into the future may have been (moderately) underestimated.[11]

There is increasing concern about the stability of the Greenland and West Antarctic Ice Sheets

- There have been further studies indicating a dynamic response of the outlet glaciers for the Greenland and West Antarctic Ice Sheets. However, these critically important dynamic responses are not included in current ice sheet models.[12, 13]
- Recent interpretations of geological data suggest that at the time of the last interglacial (~125,000 years ago), when sea level was close to today's value, there was a period when "...the average rate of sea-level rise [was] 1.6 m/century."[14] This demonstrates that sea-level rise of 1 m or more by the year 2100 is plausible.

Estimates of ocean thermal expansion have improved

- Small but important biases in historical ocean temperature observations have been detected.[15] A method for correcting these biases has now been proposed[16] yielding improved estimates of ocean thermal expansion[17]. This has allowed an improved understanding of observed sea-level rise from 1961 to 2003.[17]

Global emissions of greenhouse gases now exceed the 'high-range' A1FI IPCC scenario

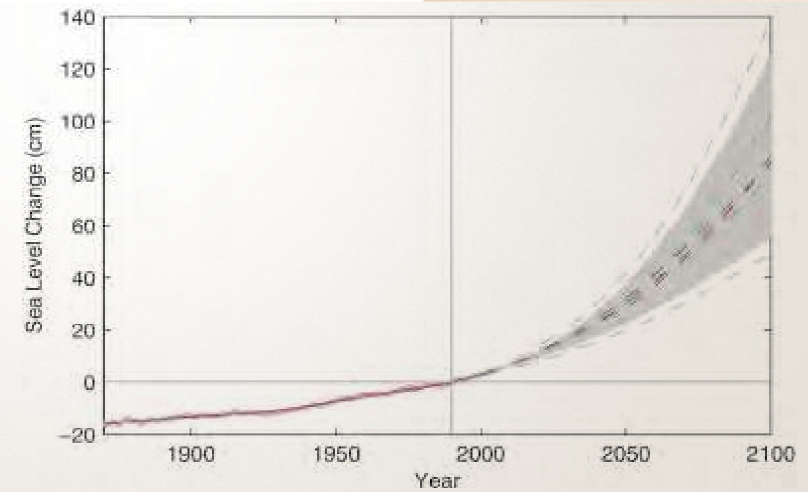
- Since 2004, global emissions of greenhouse gases have exceeded those of the 'high-range' A1FI scenario, on which the upper limit of the AR4 sea-level projections has been based.[18,19,20]

Australian sea levels

Sea level is rising around Australia

- Coastal observations confirm that sea levels have been rising around Australia since at least 1920.[21]
- Sea-level rise off the east and west coast of Australia has already resulted in extreme sea-level events of a given magnitude occurring roughly three times as often in the last half of the 20th century compared with the first half.[21]
- For many locations, a 0.5 m sea-level rise would result in the present one-in a-hundred-year event becoming an annual or more frequent event by the end of the 21st century.
- Some areas of the Australian coastline are vulnerable to serious impacts from sea-level rise and extreme events.

Figure 3.
Projected sea-level rise with one of the statistical models based on relationship of observed sea levels and surface temperatures.[8]



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5. synthesis and uncertainties

While sea-level rise is one of the most certain and important impacts of climate change, quantifying the amount of both global-averaged and regional sea-level rise remains one of the important climate change challenges.

To date, understanding of 20th century sea-level rise has not been sufficient to completely explain the observed global-averaged and regional sea-level rise. Accordingly, there has been ongoing concern about the accuracy of projections for the 21st century and beyond. Some key messages are:

- The comparison of the AR4 and TAR projections indicates that both sets of projections are similar when the qualifying statements in the AR4 are considered. The major difference is at the *low end* of the projections – the low end of the AR4 projections is higher than the low end of the TAR projections (by around 10 cm).
- The observed sea level is currently tracking near the upper end of the IPCC projections from the start date of the projections in 1990. This is not to say the observed sea levels will continue to track this line – they may diverge either above or below.
- The simple statistical models are consistent with a sea-level rise closer to (or even above) the upper end of the IPCC projections.
- Geological data indicate sea levels several metres above today's value, and average rates of sea-level rise of 1.6 m/century,[14] at a time when global average temperature was similar to projections for the end of the 21st century. These results show that a change in sea level more rapid than present projections is credible and has occurred before.
- Without significant and urgent mitigation of greenhouse gas emissions, the long-term survival of the Greenland Ice Sheet is at risk. Global average temperatures have already increased by about 0.8°C relative to the late 19th century. Based on current understanding, a further warming of just 1.1°C means that there is a 1-in-40 chance of ongoing decay of the Greenland Ice Sheet from surface melting alone. With a warming of 2.3°C above today's temperatures, this risk rises to about 50-50. This surface melting alone would take many centuries to contribute metres to sea level.[22]
- There is increasing concern about the stability of both the Greenland and the West Antarctic Ice Sheets leading to a more rapid rate of sea-level rise. While our understanding of the relevant processes is limited, it is important to recognize 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.
- Sea-level rise will continue for thousands of years after stabilization of greenhouse gas concentrations and the impacts will grow as sea levels rise. The impacts will be felt through both changes in the mean sea level and also by changes in the frequency and intensity of extreme events. Coastal erosion, particularly of sandy beaches, is expected to increase.
- Impacts from local extreme sea levels will become more frequent, with the prospect that high sea-level events now expected once in one hundred years may become annual or more frequent events by the end of the 21st century at some locations.

There remain several uncertainties in understanding and projecting global-averaged and regional sea-level rise and its impacts. Improved and more confident projections require action on a number of fronts, as documented by the World Climate Research Programme workshop on sea-level rise.[23] Immediate actions include: ongoing and enhanced observations of sea levels and the components contributing to sea-level rise; and developing improved models. These steps would give an early warning of any further acceleration in the rate of sea-level rise. Improving our monitoring, understanding and modelling of ice sheet responses to global warming is urgent.

Uncertainties are also associated with additional processes that affect the impact of sea-level rise at the coast. These may be both 'direct' (ie, vertical land motion, which directly affects sea level as observed on land) and 'indirect' (eg, changing height of storm surges or ocean waves, which changes the flooding potential of the sea). Vertical land motion may be caused by the ongoing relaxation of the Earth's crust to the melting of land ice since the last glaciation, tectonic motion, or regional and local settlement of the land surface caused by groundwater withdrawal. Indirect effects may be caused by loss of natural protecting structures such as coral reefs (eg, caused by warmer water temperatures) and beaches (eg, through sand mining or increased erosion as sea level rises). Many of these processes are poorly quantified, and an improved understanding of these additional processes is needed if we are to effectively project future impacts on low-lying coastal and island communities around Australia and elsewhere.

6. mitigation and adaptation

Avoiding the most extreme sea-level rise scenarios will require significant and urgent mitigation of greenhouse gas emissions.

A major question is whether we will pass a critical point during the 21st century that will lead to an ongoing, and possibly irretrievable, decay of the Greenland and/or West Antarctic Ice Sheets and sea-level rise of metres. Our current understanding of ice-sheet dynamics is insufficient to predict whether any such large rise would occur in a few centuries or would occur over many centuries to thousands of years and exactly what we should expect to see in coming decades.

Observations indicate that the 20th century's sea levels and rates of sea-level rise are already significantly higher than those experienced over recent centuries, the period during which major coastal developments have occurred around the world. The impacts of sea-level rise are being felt now; they will be felt during the 21st century and beyond. The effects include coastal inundation and its consequences and increased rates of coastal erosion. Impacts will be felt most acutely during extreme events. Coastal flooding events will become more severe and events of a given height will occur more frequently; indeed analysis to date indicates there has already been an increase in frequency of these flooding events.

The least-developed countries and the poor are most at risk. Environmental refugees already exist as a result of the combined impact of sea-level rise and extreme sea-level events. There will be an increase in their numbers as a result of sea-level rise during the 21st century and beyond.

Heightened expectations of Australian Government involvement in response to national and international crises and chronic problems should be anticipated.

While mitigation to avoid the worst impacts of sea-level rise is urgent, adaptation to its impacts is essential.

Planned adaptation is more cost effective and less disruptive than reactive responses to the impacts of sea-level rise, particularly those imposed during extreme events. Adaptation requires federal and state leadership as well as local and regional commitment, guided by sound science. Sound adaptation is based on sound scientific knowledge, including predictions of which regions are vulnerable and what changes they can expect. Unfortunately, at the moment sea-level projections cover a broad range, but even at the lower end, significant impacts could be expected.

Significant progress is being made on understanding of sea-level rise through results from new observing systems and reanalysis of historical data.

To improve projections, continued investment in these activities is essential and is likely to lead to a narrowing of uncertainties and improved projections in future assessments. Areas requiring additional attention include: understanding of ice sheet processes and developing a new generation of ice sheet models; understanding the regional distribution of sea-level rise; identifying changes in extreme sea level events and their causes; and quantification of the impacts of sea-level rise. A complete description of research needs is available in the World Climate Research Programme report on sea-level Rise and Variability.[23]

Appropriate strategies can significantly reduce the impacts of sea-level rise through both mitigation of our emissions and also plans to adapt to the inevitable consequences.

To address sea-level rise and its impacts requires partnerships between science, government, business and community sectors. These partnerships are required now and will need to be strengthened during the 21st century.

Photo: John Hunter

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References

1 IPCC (2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York

2 IPCC (2001). *Climate Change 2001: The Scientific Basis* (eds. J.T. Horton *et al*). Cambridge University Press.

3 J.A. Church, N. J. White, R. Coleman, K. Lambeck and J.X. Mitrovica (2004). Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate*, 17: 2609-2625.

4 J.A. Church and N.J. White (2006). A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33: L01602, doi:10.1029/2005GL024826.

5 S.J. Holgate and P.L. Woodworth (2004). Evidence for enhanced coastal sea-level rise during the 1990s, *Geophysical Research Letters*, 31: L07305, doi:10.1029/2004GL019626.

6 B. D. Beckley, F.G. Lemoine, S.B. Lutchke, R.D. Ray and N.P. Zelensky (2007) A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geopysical Resarch Letters* 34: L14608

7 S. Rahmstorf, A. Cazenave, J.A. Church, J.E. Hansen, R. Keeling, D.E. Parker and R.C.J. Somerville (2007). Recent climate observations compared to projections. *Science*, 316: 709. doi: 10.1126/science.1136843.

8 S. Rahmstorf (2007) A semi-empirical approach to future sea-level rise. *Science,* 315: 368-370.

9 R. Horton, C. Herweijer, C. Rosenzweig, J. Liu, V. Gornitz and A.C. Ruane (2008). Sea level rise projections for Current generation CGCMs based on the semi-empirical method. *Geophysical Research Letters*, 35: L02725, doi:10.1029/2007GL032468.

10 J. Hunter (2006). personal communication.

11 M.F. Meier, M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R.S. Anderson, S.P. Anderson and A.F. Glazovsky (2007). Glaciers dominate eustatic sea-level rise in the 21st century. *Science,* 317: 1064-1067

12 I.M. Howat, I.R. Joughin and T.A. Scambos (2007). Rapid change in ice discharge from Greenland outlet glaciers. *SciencExpress*,10.1026/Science.1138478

13 E. Rignot, J.L. Bamber, M.R. van den Broeke, C. Davis, Y. Li, W.J. van de Berg and E. van Meijgaard (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modeling. *Nature Geoscience*, 1: 106-110.

14 E.J. Rohling, K. Grant, CH. Hemleben, M. Siddall, B.A.A. Hoogakker, M. Bolshaw and M. Kucera (2008). High rates of sea-level rise during the last interglacial period. *Nature Geoscience*, 1: 38-42.

15 V. Gouretski,and K.P. Koltermann (2007). How much is the ocean really warming? *Geophysical Research Letters* 34: L01610, doi:10.1029/2006GL027834

16 S.J. Wijffels, J. Willis, C.M. Domingues, P. Barker, N. White, A. Gronell, K. Ridgway and J. Church (2008). Changing expendable bathythermograph fall-rates and their impact on estimates of thermosteric sea-level rise. *Journal of Climate*, doi:10.1175-2008JCL12290.1 (in press).

17 C.M. Domingues, J. A. Church, N. J. White, P. Gleckler, S. E. Wijffels, P. M. Barker and J.R. Dunn (2008). Improved estimates of ocean-warming and multi-decadal sea-level rise. *Nature*, 453: 1090-1094. doi:10.1038/nature07080.

18 M.R. Raupach, G. Marland, P. Ciais, C. Le Quéré, J.G. Canadel, G. Klepper, C.B. Field (2007). Global and regional drivers of accelerating CO_2 emissions. *Proceedings National Academy of Sciences,* 104: 10288–10293.

19 J.G. Canadell, C. Le Quéré, M. R. Raupach, C. B. Field, E. T. Buitehuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton and G. Marland (2007). Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings National Academy of Sciences*, 104, 18866-18870.

20 http://www.globalcarbonproject.org/global/pdf/GCP_CarbonCycleUpdate.pdf

21 J.A. Church, J. R. Hunter, K. McInnes and N. J. White (2006). Sea-level rise around the Australian coastline and the changing frequency of extreme events. *Australian Meteorological Magazine*, 55: 253-260.

22 J.M. Gregory and P. Huybrechts (2006) Ice-sheet contributions to future sea-level change. *Phil. Trans. R. Soc.* A 364, 1709–1731

23 Available at http://wcrp.wmo.int/AP_SeaLevel.html

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