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SEA LEVEL RISE
Emerging Issues

Summary

When the Earth was warmer, global sea levels were several metres higher than at present. Global warming results in rising oceans. There is now increasingly rapid melting of polar ice sheets and mountain glaciers. Scientific understanding of how climate change is driving sea level rise has improved in the past four years and recent estimates of future rise are greater than those assessed in previous Intergovernmental Panel on Climate Change (IPCC) reports. However, the estimates still have wide ranges due to uncertainty in knowing how rapidly the movement and melting of polar ice sheets will increase.

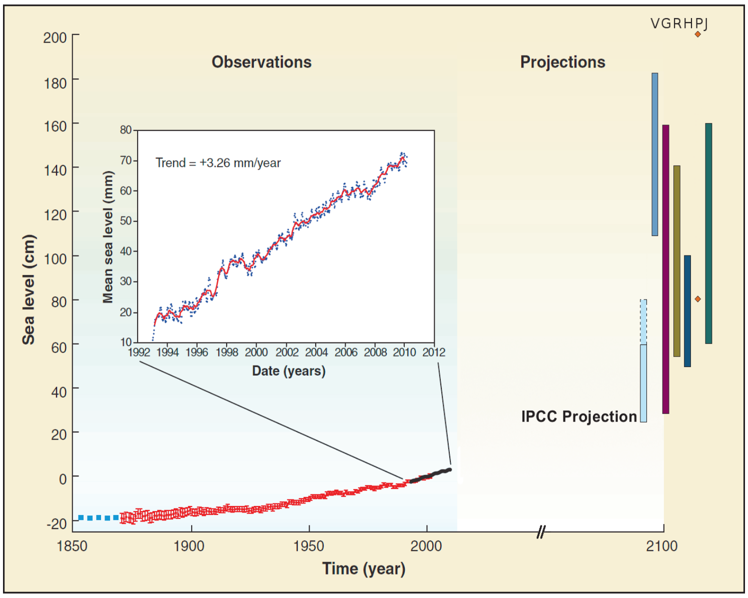

Figure 1: Global mean sea level rise

The red curve shows data from tidal gauges; the black curve shows more recent satellite measurements. The projections for 2100 show IPCC projections in blue. However, the IPCC could not provide an upper bound at that time (the dotted section shows an example of how dynamic ice behaviour could alter the IPCC projections). The other projections are taken from Vermeer, Grinsted, Rahmstorf, Horton, Pfeffer, and Jevrejeva , in that order and detailed in Table 2. Pfeffer's paper presents two values for rise rather than a range, the lower considered more likely than the upper. Reprinted with permission from AAAS.[10]

Warmer climates have always resulted in higher seas

The geological record shows that warmer climates have always been linked with higher seas because glaciers and ice sheets melt and add their water to the oceans. Since the end of the last Ice Age, 20,000 years ago, global sea levels rose by around 120 metres to current levels while global average surface temperatures warmed by around 6°C.[1,2]

There is also clear evidence that sea level can be higher than it is now, as it was during the Last Interglacial period (~125,000 years ago). Sea level rose around five metres (and possibly more) above present-day values as a result of warming that is comparable to what is expected in the Twenty-First century.[1,3] While there is less information about the rates at which sea level rose in this period, some studies indicate that these exceeded 1.5 metres per century.[4,5]

Sea levels have risen throughout the Twentieth Century

Tidal records from many sites around the globe provide clear evidence that sea levels have risen over the last century by an average of 1.7 mm/yr (± 0.5 mm/yr).[6] Over the period of satellite observation, altimetry and tidal records confirm that the rate has increased, as shown in Figure 1. The rise over the past fifteen years has been 3.3 mm/yr (± 0.4 mm/yr).[7]

Accounting for land movement, comparable rises are seen in the tidal records for Auckland, Wellington, Dunedin, and Lyttelton where annual records cover most of last

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[1] Jansen, E., J.*et al* Chapter 6.4, "Climate Change 2007: Working Group I" Fourth Assessment Report, Intergovernmental Panel on Climate Change, 2007

[2] Schneider von Deimling, T., *et al* "How cold was the Last Glacial Maximum?", Geophysical Research Letters, 33,:L14709, doi:10.1029/2006GL026484, 2006

[3] R. E. Kopp, *et al* " Probabilistic assessment of sea level during the last interglacial stage", Nature 462: 863-867, doi:10.1038/nature08686, 2009

[4] E. J. Rohling, *et al* "High rates of sea-level rise during the last interglacial period", Nature Geoscience, 1:8, doi:10.1038/ngeo.2007.28, 2007

[5] W. H. Berger "Sea level in the late Quaternary: patterns of variation and implications", International Journal of Earth Sciences 97:1143, doi 10.1007/s00531-008-0343-y, 2008

[6] Bindoff, N. L. *et al* Chapter 5, "Climate Change 2007: Working Group I" Fourth Assessment Report, Intergovernmental Panel on Climate Change, 2007

[7] Cazenave, A., Llovel, W. "Contemporary Sea Level Rise", Annual Review of Marine Sciences, 2:145, doi:10.1146/annurev-marine-120308-081105, 2010

century. The rise around New Zealand has been close to the global trend.[8] However, evidence of an accelerating rate has not yet been seen in the New Zealand tidal record.[9]

Projections of sea level rise have changed dramatically over the last four years

The causes of sea level rise over most of the past fifty years have recently become better understood, the rise being driven by thermal expansion of oceans due to warming and the loss of land-based ice on Greenland and Antarctica and on mountains.[10,11]

The IPCC's 2007 report presented model results suggesting a global sea level rise for 2090-99 compared to 1980-99 of 18 -59 cm, with a caveat of a further 10-20 cm covering some ice-sheet contributions. There was insufficient evidence to include the effects of possible future rapid dynamical changes in ice flow and the IPCC stated that "the upper values of the ranges given are not to be considered upper bounds for sea level rise".[12]

Over the past four years, researchers have made progress in understanding polar ice sheet processes, informed largely by rapidly improving satellite observations. As yet, these processes are not included in mechanistic models of ice sheet behaviour. In the absence of such robust models, researchers have relied upon simple semi-empirical approaches – extrapolating from past temperature and sea level records. There is a wide range in these projections because of current limits of understanding. A key research goal is to develop models that properly simulate the important physical processes and supersede the semi-empirical approaches. Figure 1 shows several recent projections for 2100. However, our limited understanding does not yet allow us to be certain about the probability of a given rise by a given time.

Melting of polar ice sheets will drive sea level rise but the maximum rate of ice loss is uncertain

Key to the uncertainty about the rate of sea level rise is the behaviour of the vast ice sheets covering Antarctica and Greenland. Ice loss from Greenland and West Antarctica may become the predominant driver of sea level rise towards the end of this century and beyond.[13] Several studies suggest there has been an increasing rate of ice loss over the last two decades and recent changes are shown in Figure 2.[7,14]

Researchers are only starting to quantify the processes that change the rates of loss from ice sheets as temperature rises. Floating ocean ice shelves can hold back on-shore ice but are susceptible to sudden disintegration. Thinning ice at the margins of ice sheets allows warmer water to penetrate under ice sheets where the bedrock is below sea level. These processes are difficult to model with numerous possible positive feedbacks (and few negative feedbacks). The data to inform these models are also currently limited and difficult to measure. For example, many of these processes depend upon the land profile at the base of polar ice sheets and upon the temperature of water under floating ice sheets. The rate at which polar oceans will warm and the distribution of that warming is uncertain and will affect the rate of ice sheet loss.

Most new estimates of sea level rise are based on models that use past behaviour as a guide to future ice sheet loss and consequent sea level rise.[15-19] This approach assumes that future behaviours will be driven by the same factors as past behaviour, an assumption that may not hold.[20] However, these models project rises that are physically plausible and comparable to those seen in the Last Interglacial. Another approach uses present observations of the maximum speeds of glaciers to justify "physically plausible" rates of ice sheet loss.[13] These approaches have

Source	1961-2003 contribution mm/yr [11]	1993-2007 contribution mm/yr [7]	Relationship with global warming
Polar ice sheets	0.5 ± 0.2	0.7 ± 0.2	Poorly known Likely to increase with warming
Thermal expansion	0.52 ± 0.08	1.0 ± 0.3	Well known, increasing with warming
Other land-based ice		1.1 ± 0.25	Well known, increasing with warming
Dams and ground-water pumping	Variable but small	Close to zero	Dependent upon human response to warming
Modelled sum of sources	1.5 ± 0.4	2.85 ± 0.35	
Observed rise	1.6 ± 0.2	3.3 ± 0.4	

Table 1: A summary of explanations of current global sea level rise

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[8] Hannah, J. "An updated analysis of long-term sea level change in New Zealand", Geophysical Research Letters, 31:03307, doi:10.1029/2003GL019166, 2004

[9] Hannah, J. University of Otago, personal communication

[10] Nicholls, R.J., Cazenave, A. "Sea-Level Rise and Its Impact on Coastal Zones", Science, 328: 1517, doi:10.1126/science.1185782, 2010

[11] Domingues, C.M, *et al* "Improved estimates of upper-ocean warming and multi-decadal sea-level rise", Nature 453:1090-93, doi:10.1038/nature07080, 2008

[12] "Climate Change 2007: Synthesis Report", Fourth Assessment Report, Intergovernmental Panel on Climate Change, 2007

[13] Pfeffer, W.T., *et al* "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise", Science, 321:1340, doi: 10.1126/science.1159099, 2008

[14] Velicogna, I. "Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE", Geophysical Research Letters, 36:19503, doi:10.1029/2009GL040222, 2009

[15] Rahmstorf, S. *et al* "A Semi-Empirical Approach to Projecting Future Sea-Level Rise", Science, 315:368, doi:10.1126/science.1135456, 2007

[16] Horton, R. *et al* "Sea level rise projections for current generation CGCMs based on the semi-empirical method", Geophysical Research Letters, 35:02715, doi:10.1029/2007GL032486, 2008

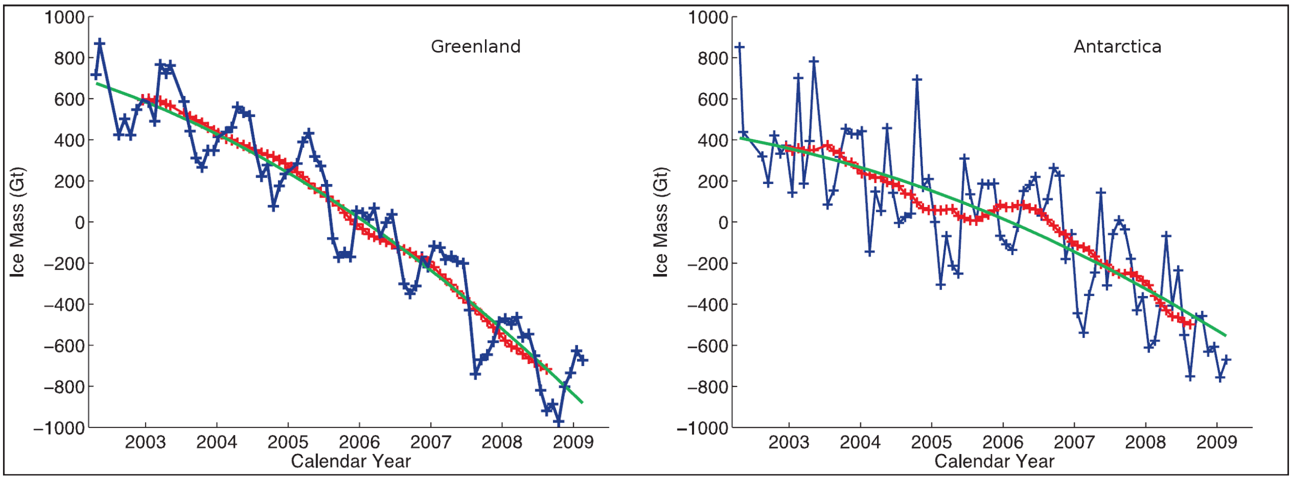

Figure 2: Recent polar ice loss.
Estimates of loss from ice sheets, from measurements by the GRACE satellites. Blue crosses are unfiltered data, red and green show filtered trends.[13]

also been backed up by new and consistent estimates of the rate at which sea level rose during the Last Interglacial.[4] Figure 1 shows several projections made using a variety of methods. With the inclusion of dynamic ice sheet behaviour, all extend substantially above the model projections without future rapid changes in dynamic behaviour from the IPCC's Fourth Assessment Report.

The connection between the rate of temperature rise and the rate of ice loss is another question which currently cannot be answered with certainty. There may be limits to the rate of ice sheet melt in a warmer world, or ice sheets may influence their own behaviour and set their own speed for ice loss.[20] There is no reason to think that higher temperatures could lead to a slower rate of sea level rise.

Non-polar ice loss adds to sea level rise

Smaller ice caps and glaciers in the major mountain ranges, including those in New Zealand, have a simpler and better understood response to warming than do polar ice sheets. The current contribution of these glaciers to sea level rise is similar to that of thermal expansion but the maximum total rise from this source is estimated to be around 0.35 metres before the majority of non-polar glaciers are lost.[7]

Source	Sea level rise by 2100 (m)
Pfeffer[13]	0.8 plausible (2.0 maximum possible)
Rahmstorf[15]	0.5 - 1.4
Horton[16]	0.5 - 1.0
Grinstead[17]	0.3 - 2.2
Vermeer[18]	0.75 - 1.9
Jevrejeva[19]	0.6 - 1.6

Table 2: Recent scientific projections of sea level rise by 2100

Thermal expansion of the oceans makes a simpler contribution

The other main cause of sea level rise is easier to predict — as the oceans heat up, they expand and this expansion increases as ocean temperatures increase. This rise is becoming better understood as ocean models improve and use the increasing amounts of data available from satellites, deep ocean probes, and ocean buoys.

The rise will depend upon the magnitude of warming that occurs, which in turn depends upon global emissions of greenhouse gases. Greenhouse gas emissions have been in the upper end of the range of IPCC emissions scenarios over the last decade.[21] Even with a halving of global emissions by 2050, there is still a substantial chance of warming above 2°C by 2100.[22] Thus the world is already committed to substantial warming and a consequent future sea level rise due to thermal expansion.[23]

New Zealand's tectonics may be fast enough to alter local sea level rise risks

While, within the limits of present measurement capability, the majority of the New Zealand landmass appears to be relatively stable (despite an expected rise due to a slow adjustment following the last Ice Age), earthquake activity can quickly alter this situation. While the long-term ongoing tectonic effect is small when compared with changes in ocean height, the data we have do not allow us to rule out local changes of height which may increase local risks in areas where strong subsidence is taking place.[8, 24]

Recent research presents a range of projections above existing guidance

Climate change may cause several metres of sea level rise over the next thousand years.[23] For the decades and centuries that are important for planning purposes, we cannot yet state the likelihood of a given rate of sea level

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17 Grinstead, A., *et al* "Reconstructing sea level from paleo and projected temperatures 200 to 2100AD", Climate Dynamics, 34:461, doi:10.1007/s00382-008-0507-2, 2009

18 Vermeer, M. *et al* "Global sea level linked to global temperatures", Proceedings of the National Academy of Sciences, 106:21527-21532, doi:10.1073 pnas.0907765106, 2009

19 Jevrejeva, S., *et al* "How will sea level respond to changes in natural and anthropogenic forcings by 2100?" Geophysical Research Letters, 37:07703 doi:10.1029/2010GL042947, 2010

20 Lowe, J.A, Gregory, J.M. "A sea of uncertainty" Nature Reports 4: 42 doi:10.1038/climate.2010.30, 2010

21 Manning, M., *et al* "Misrepresentation of the IPCC CO_2 emission scenarios" Nature Geoscience, 3:376-377, 2010

Source	Sea level rise by 2100 (m)
Department of Climate Change, Australia[26]	0.6 m plausible, 1.5 m “cannot be ruled out”, risk assessment level 1.1 m
Dept of Environment, Climate Change & Water, NSW[27]	0.9 m
Department of Environment & Resource Management, Queensland[28]	0.8 m
California Climate Change Center, USA[29]	1.0 - 1.4 m by 2100
DEFRA, UK[30]	0.12 - 0.76 m, extreme scenario 1.9 m
Deltacommissie, The Netherlands[31]	0.55 - 1.2 m, planning level 1.1 m
United Nations Environment Programme[32]	0.5 - 1.4 m
Climate Change Research Centre, UNSW[33]	Double IPCC estimates
International Alliance of Research Universities[34]	0.5 - 1.5 m

Table 3: Recent international projections of sea level rise by 2100 relevant to coastal planning

rise. However, our uncertainty is mostly one-sided, with more possible effects that might hasten sea level rise than might slow it.

New research has generated a range of projected rises that are considered reasonable, and rises considered plausible. Risk management is becoming important as a way of combining the range of potential future changes with the cost of their impacts and this provides a clear basis for taking account of the upper side of estimated ranges. This approach can allow for planning that does not lock in vulnerability, should an extreme scenario occur. Existing Ministry for the Environment guidance reflects this approach (0.5 metres is considered as a base rise by 2090-2099, “along with an assessment of the potential consequences from a range of possible higher sea-level rises… all assessments should consider the consequences of… at least 0.8 m”, with further rise expected beyond 2100.[25] That guidance was based on the IPCC Fourth Assessment Report and science available to 2008 (which included the first Rahmstorf & Horton estimates in Table 2); more recent research has suggested the ranges of values shown by the last four estimates in Table 2. Other international work being used for coastal planning, vulnerability analysis, engineering design, and scientific advice is summarised in Table 3.

Sea level rise compounds known coastal hazards

Twelve of New Zealand’s fifteen largest towns and cities are coastal. They are already exposed to coastal hazards from current climate variability and weather events: coastal erosion; flooding from storm surges, waves and swell, king tides, and extreme rainfall; and salt intrusion into groundwater. Sea level rise will compound these hazards both in terms of frequency and intensity of hazards. Several city and regional councils have projects underway to quantify the change to these hazards. We have a good understanding of many processes involved in existing threats, and past data to guide risk assessment. However, sea level rise adds another dimension to consider in such risk assessments because the magnitude and rate of rise is poorly known, as is the way in which our coastline may respond these changes.

Contributors and Reviewers

Dr John Beavan, Dr Rob Bell, Dr Robert Bindschadler, Dr John Church, Prof John Hannah, Prof Keith Hunter, Assoc Prof Paul Kench, Dr Andrew Mackintosh, Prof Martin Manning, Prof Tim Naish, Doug Ramsay, Richard Reinen-Hamill, Dr Andy Reisinger, Dr James Renwick, Zach Rissel, Prof Caroline Saunders, Dr David Wratt, Dr Dan Zwartz

For further information, please contact

Dr Jez Weston
Jez.weston@royalsociety.org.nz

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33 Climate Change Research Centre, University of New South Wales “The Copenhagen Diagnosis”, 2009

34 International Alliance of Research Universities “Synthesis Report from Climate Change, Global Risks, Challenges & Decisions”, 2009