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Sea-level Rise and Variability

A summary for policy makers

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The book stems from a workshop on sea level rise and variability held under the auspices of the World Climate Research Programme at the Intergovernmental Oceanographic Commission of UNESCO in Paris in 2006. The aim of the workshop was to bring together all relevant scientific expertise with a view towards identifying the uncertainties associated with past and future sea-level rise and variability, as well as the research and observational activities needed for narrowing these uncertainties. The workshop was attended by 163 scientists from 29 countries representing a wide range of expertise and supported by 34 organisations. More information about the workshop and the recommendations concerning observation needs are available at: http://copes.ipsl.jussieu.fr/Workshops/SeaLevel/Reports/Summary_Statement_2006_1004.pdf

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THE ISSUE

Coastal zones have changed profoundly during the 20th century with increasing populations, economies and urbanization. Today, low-elevation coastal zones below 10-m elevation contain about 10% of the world population (McGranahan et al., 2007). In the 136 port cities around the world with more than 1 million inhabitants there is a total population of 400 million people, of which about 10% are exposed to a 1 in 100 year coastal flood event (Nicholls et al 2008).

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) indicates a range between 0.18-0.79 m of sea-level rise, including an allowance for a contribution from a potential rapid dynamic ice-sheet response, between 1980-2000 and 2090-2100. The Assessment also emphasizes that the contribution from changes in ice dynamics is highly uncertain and a larger rise cannot be excluded.

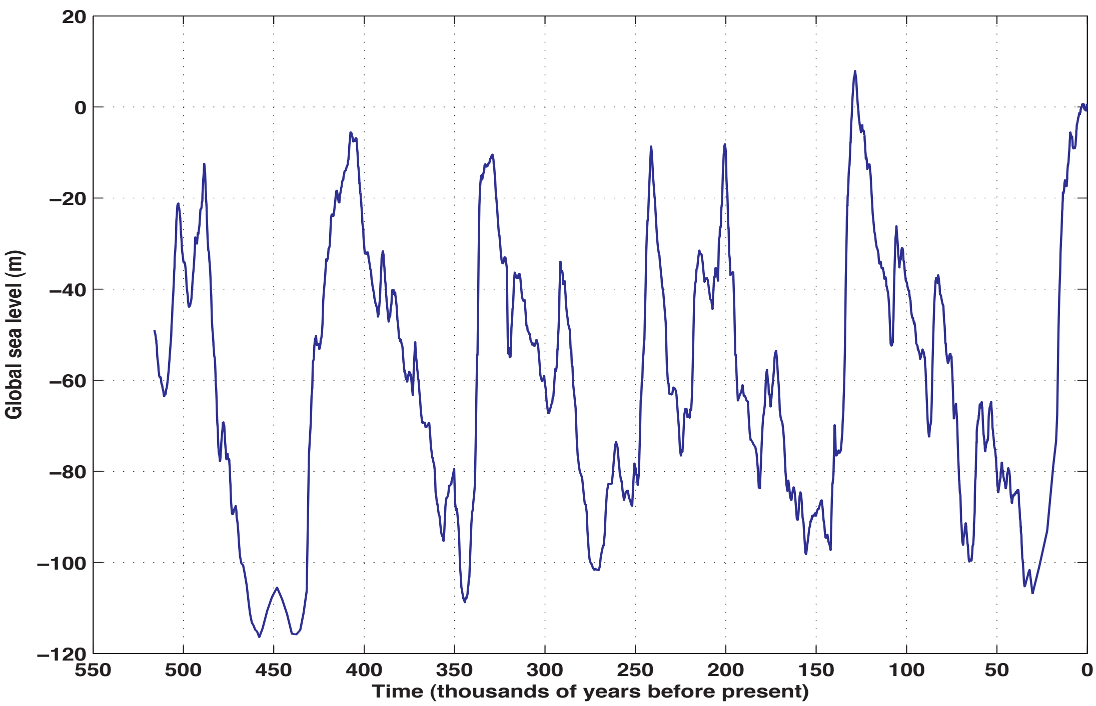
With coastal development continuing at a rapid pace, society is becoming increasingly vulnerable to sea-level rise and variability as Hurricane Katrina demonstrated in New Orleans in 2005. Other aspects of climate change and land subsidence significantly exacerbate this effect though the relative importance of these factors varies from location (Nicholls and Cazenave, 2010).

Improved understanding of sea-level rise and variability is required to reduce the uncertainties associated with sea-level rise projections, and hence to contribute to more effective coastal planning, management and adaptation in the presence of the many pressures on coastal regions.

SEA LEVEL HAS CHANGED BY OVER 100 m DURING GLACIAL CYCLES

Over the glacial cycles of the last million years, sea level has oscillated by more than a hundred metres as the ice sheets, particularly those of northern Europe and North America waxed and waned (Figure 1). These changes in sea level and the related global average temperature changes were initiated by changes in the solar radiation reaching the Earth's surface (as a result of variations in Earth's orbit around the sun and in the orientation of the Earth's axis) and amplified by feedbacks associated with changes in the Earth's albedo and greenhouse gas concentrations.

Fig. 1. Sea level over the last 500 000 years compared to present day sea level. This sea-level estimate is from Rohling et al. (2009) and is based on carbonate $\delta^{18}O$ measurements in the central Red Sea as these give a more continuous time series compared with the direct paleo inferences of sea level.



Global temperatures similar to those expected in the latter part of the 21st century occurred during the last interglacial, about 125 thousand years ago. At that time, paleo data indicates rates of sea-level rise of about 6 to 9 m/millenia with sea level reaching 6–9 m above present day values and with polar temperatures about 3°C to 5°C higher than today. These warmer conditions may serve as a useful analogue for the 21st century and beyond.

Over the following hundred thousand years, sea level fell to about 130 m below today's values as the northern European and American ice sheets formed. From twenty thousand years ago to about seven thousand years ago these ice sheets collapsed, and sea level rose rapidly at average rates of 1 m/century for many millennia, with peak rates during the deglaciation potentially exceeding several metres per century. From about six to two thousand years ago, sea level rose more slowly. Over the last two thousand years up to the 18th century, paleo sea level data indicate low rates of sea-level change.

THE RATE OF SEA-LEVEL RISE HAS INCREASED

Coastal sediment cores and other paleo sea-level data, the few long (pre-1900) tide-gauge records, reconstructions of 20th century sea levels and satellite-altimeter data all indicate that the rate of sea-level rise has increased by about an order of magnitude – from at most a few tenths of a millimeter/year over previous millennia to about 1.7 mm/year during the 20th century. Since 1993, the rate has been over 3 mm/year, greater than any similar length period during the 20th century (Figure 2).

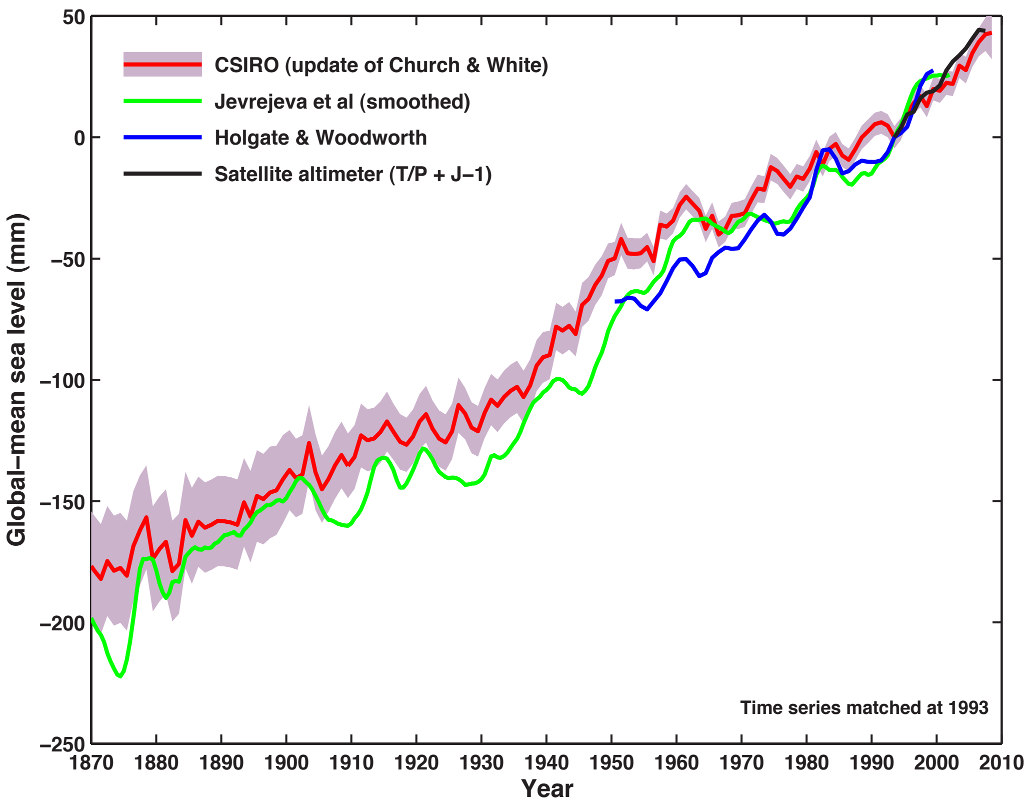


Fig. 2. Global mean sea level from 1870 to 2008 with 1 standard deviation error estimates updated from Church and White (2006; red), from Jevrejeva et al. (2006; green) and from 1950 to 2000 from Holgate and Woodworth (2004; blue). The TOPEX/Poseidon/Jason-1 and -2 global mean sea level (based on standard processing as in Church and White 2006) from 1993 to 2008 is in black. All series have been set to a common value at the start of the altimeter record in 1993.

Many different physical processes contribute to sea level change and none of these produce a spatially uniform signal (Figure 3). On decadal time scales the dominant contributions are (i) the melting of glaciers and ice caps (which has increased in the 1990s) and (ii) upper ocean thermal expansion, with smaller but significant contributions from deep-ocean thermal expansion and the ice sheets. Sea level also changes as a result of storage of water in dams and extraction of water from aquifers. For the period 1961-2006, Domingues et al. (2008) have produced an approximate explanation for the observed rise (Figure 4; Table 1) by combining revised estimates for upper-ocean thermal expansion and glacier and ice-cap contributions with reasonable but less certain estimates of contribution from deep-ocean thermal expansion and the Greenland and Antarctic Ice-Sheets.

The use of satellite altimetry to measure changes in ocean and ice sheet volume, satellite gravity to measure changes in ocean and ice sheet mass, and Argo profiling floats to measure changes in upper-ocean temperatures and thermal expansion are leading to improved understanding of the sea-level budget since 2003. Analysis of these and other observations indicate an increasing mountain glacier and ice cap contribution and also increasing Greenland and Antarctic ice-sheet contributions as a result of the flow of ice into the ocean from both Greenland and Antarctica. Of particular concern is the rapid dynamic thinning of the margins of the Greenland and Antarctic Ice Sheets. However, the record is still short, some discrepancies remain and physically based quantitative estimates for the 21st century are incomplete at present.

Improved understanding of the contributions to sea-level rise is important as it is likely to lead to better observational constraints on the climate models used for projections of sea-level rise in the IPCC Fifth Assessment Report (due in 2013-14).

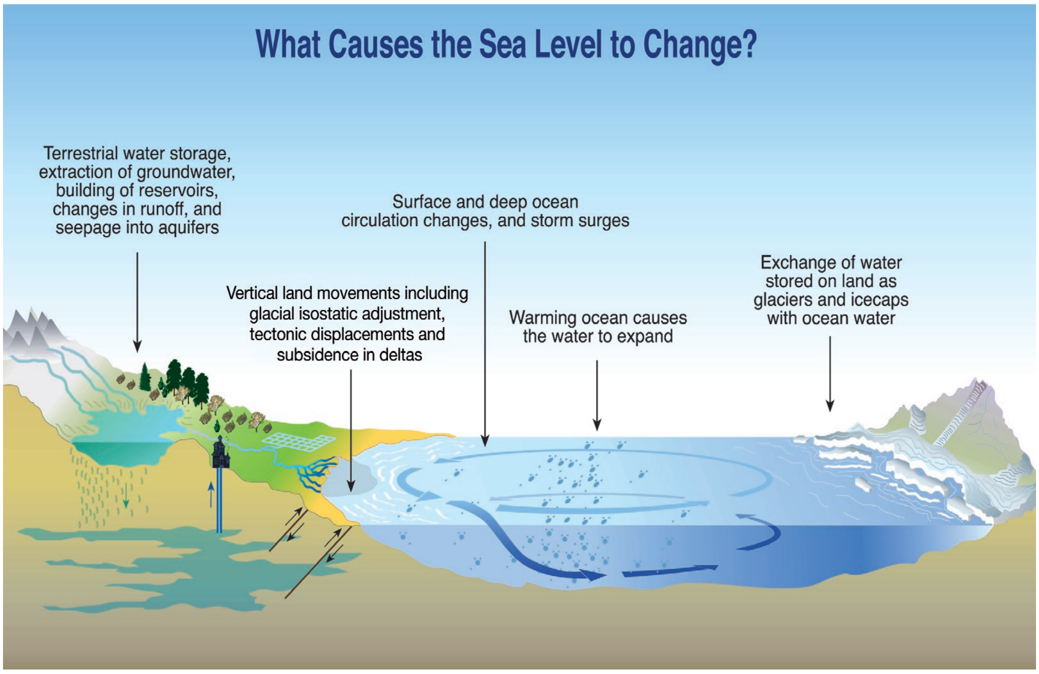


Fig. 3. Processes that contribute to sea level change. *Adapted from* Causes of sea level rise from climate change (2002). *In UNEP/ GRID-Arendal Maps and Graphics Library. http:// maps.grida.no/go/graphic/ causes-of-sea-level-rise-from-climate-change).*

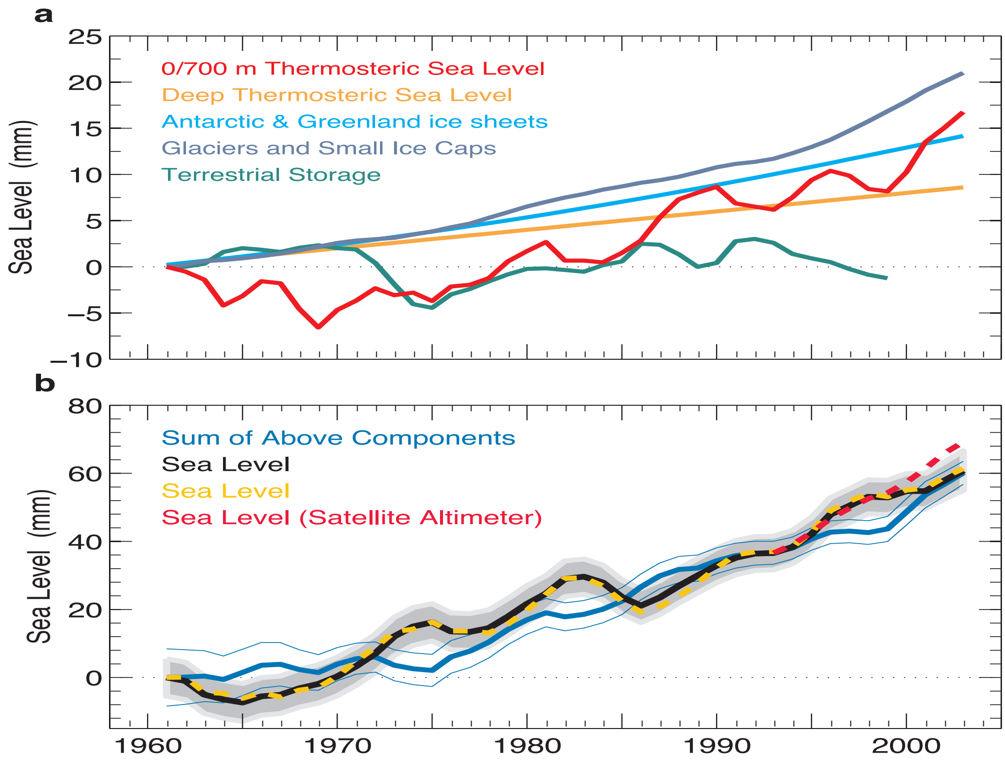


Fig. 4. Total observed sea-level rise and its components. (a) The components are thermal expansion in the upper 700m (red), thermal expansion in the deep ocean (orange), the ice sheets of Antarctica and Greenland (cyan), glaciers and ice caps (grey), and terrestrial storage (green). (b) The sum of the contributions is shown by the blue line. For the sum of contributions, the estimates of 1 standard deviation error for upper ocean thermal expansion are shown by the thin blue lines.

The estimated sea levels are indicated by the black line from Domingues et al. (2008), the yellow dotted line from Jevrejeva et al. (2006), and the red dotted line from satellite altimeter observations. Estimates of 1 standard deviation error for the sea level are indicated by the grey shading.

All time series were smoothed with a 3-year running average and are relative to 1961 (from Domingues et al. 2008).

Table 1 Contributions to sea-level rise for the period 1961 to 2003, from Domingues et al. 2008).

Contribution	Amount of rise
Ocean thermal expansion for the upper 700 m	0.5 ± 0.1 mm/year
Ocean thermal expansion below 700 m	0.2 ± 0.1 mm/year
Glaciers and ice caps	0.5 ± 0.2 mm/year
Greenland Ice Sheet	0.1 ± 0.1 mm/year
Antarctic Ice Sheet	0.2 ± 0.4 mm/year
Sum of contributions	**1.5 ± 0.4 mm/year**
Observed sea-level rise	**1.6 ± 0.2 mm/year**

THE REGIONAL DISTRIBUTION OF SEA-LEVEL RISE

The regional distribution of sea-level rise is important because it is the regional or local sea-level change and local land motion that most directly impacts society and the environment. Satellite altimeter data show significant regional variations in the rate of sea-level rise (Figure 5), with some regions having experienced about five times the global-averaged rate of rise since 1993. However, this regional variation in the relatively short altimeter record is largely a result of climate variability, particularly in the equatorial Pacific Ocean. The pattern is associated with the movement of water within the oceans in response to varying wind patterns associated with climate phenomena like the El Niño-Southern Oscillation and is largely reflected in regional patterns of ocean thermal expansion.

During the 21st century, climate variability will continue and coastal communities will be impacted by the combination of the pattern of long-term sea-level rise, the natural variability in sea level and of course extreme sea level events caused by storms and waves.

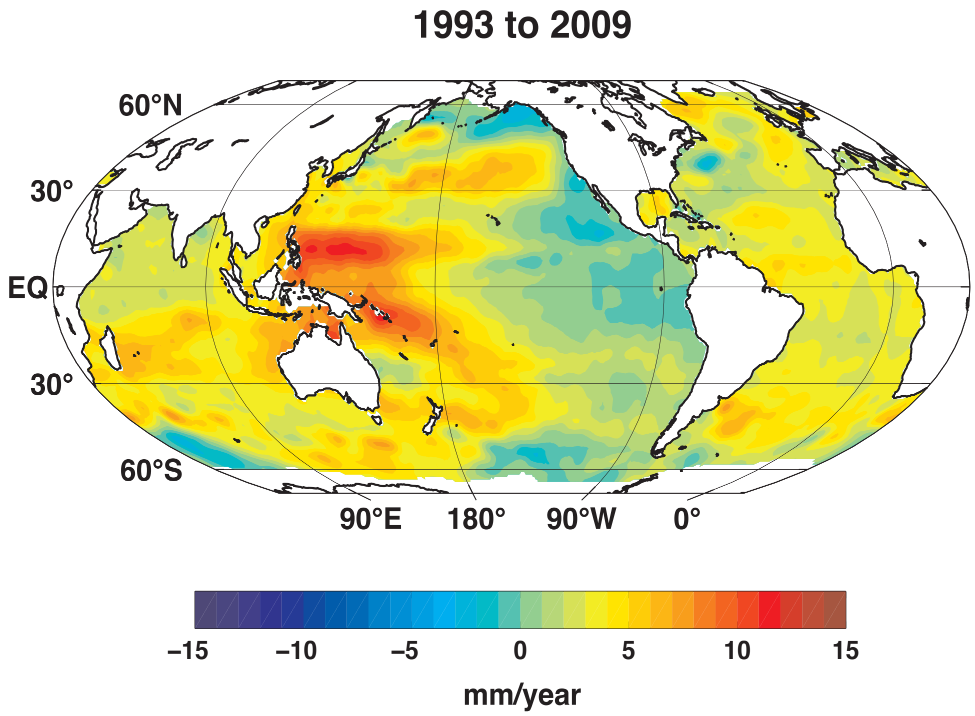


Fig. 5 . The spatial distribution of the rates of sea-level rise, plotted about the global averaged rate of rise for the period January 1993 to December 2009, as measured from satellite altimeter data (available at http://www.cmar.csiro.au/sealevel/).

Changes in the mass of the ice sheets (and glaciers and ice caps) also influence the regional distribution of sea-level rise through corresponding changes in the Earth's gravitational field and the elastic movement of the Earth's crust. As a result, the contribution from the ice sheets results in a lower relative sea level near decaying ice sheets and a larger than the globally averaged rise (up to about 20%) far from the decaying ice sheets. Thus, ice sheet contributions to future sea-level rise may have a disproportionate impact in some far field and potentially vulnerable regions.

IPCC PROJECTIONS OF SEA-LEVEL RISE FOR THE 21ST CENTURY ARE SIMILAR IN THE THIRD AND FOURTH ASSESSMENT REPORT

The Third IPCC Assessment Report (IPCC, 2001; TAR) presented average model projections for 2100 compared to 1990 for the full range of greenhouse gas scenarios and this amounts to 30–50 cm (dark shading in Figure 6). 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, is for a sea-level rise of 9–88 cm (outer black lines).

The Fourth IPCC Assessment Report (IPCC, 2007; AR4) model projections are composed of two parts. The first part consists of the estimated sea-level rise (with a 90% confidence range) from ocean thermal expansion, glaciers and ice caps, and modelled ice sheet contributions represents a sea-level rise of 18–59 cm in 2095 (the magenta bar). This contribution is similar to, but slightly smaller than, the equivalent range from the TAR (the light shaded region). The second part consists of a possible rapid dynamic response of the Greenland and West Antarctic Ice Sheets, which could result in an accelerating contribution to sea-level rise. Recognising this possible contribution, an *ad hoc* estimation for a dynamic response of the ice sheets was made resulting in an additional allowance of 10–20 cm of sea-level rise (the red bar). However, as there was insufficient understanding of this dynamic response, this additional contribution was not included in the AR4 range of projections noted above because adequate models for quantitative estimates were not available. The IPCC (2007) also clearly stated that a larger contribution could not be excluded.

When compared in this way, the TAR and AR4 projections of sea-level rise for the 21st century are similar, especially at the upper end of the projected range.

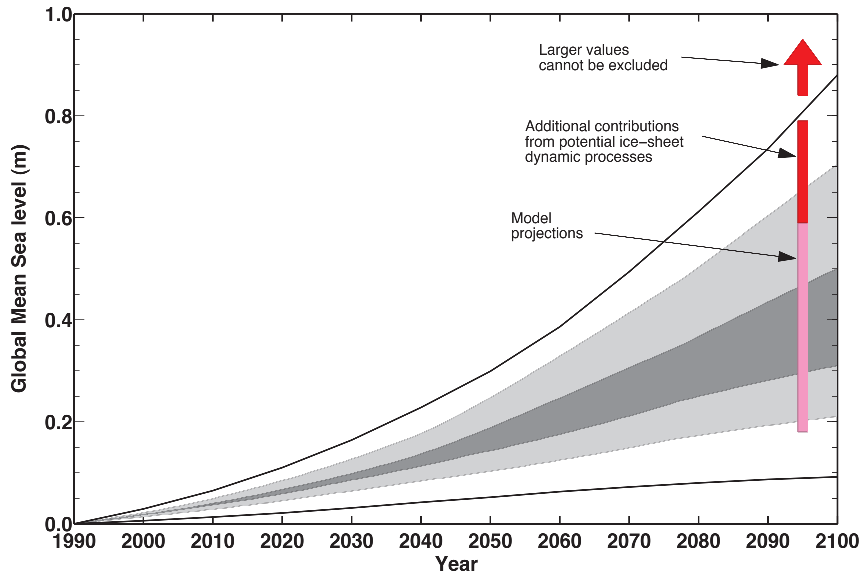


Fig. 6. Projected sea-level rise for the 21st century. The projected range of global averaged sea-level rise from the IPCC (2001) assessment report for the period 1990–2100 is shown by the lines and shading (the dark shading is the model average envelope for the range of greenhouse gas scenarios considered, the light shading is the envelope for all models and for the range of scenarios, and the outer lines include an allowance for an additional land-ice uncertainty). The AR4 IPCC projections (90% confidence limits) made in 2007 are shown by the bars plotted at 2095, the magenta bar is the range of model projections, and the red bar is the extended range to allow for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic Ice Sheets to global warming. The red arrow indicates that "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"; from Church et al. (2008).

SEA LEVEL IS CURRENTLY TRACKING THE UPPER END OF THE PROJECTIONS

Recent observations from satellite altimeters from 1993 to 2006 (Figure 7) and from coastal sea-level measurements from 1990 to 2001 (Rahmstorf et al. 2007) demonstrate that sea levels, are tracking close to the upper bound of the TAR projections of 2001. This is also equivalent, as shown above, to the upper bound of the AR4 projections of 2007, after the allowance for land–ice uncertainties is included. Recent altimeter measurements indicate sea level is continuing to rise at a rate near the upper bound of the projections since 1993. These observations do not necessarily indicate that sea level will continue to track the upper edge of the projections; it may diverge above or below these values as a result of natural and/or anthropogenic climate change.

Recognising that sea level is currently rising near the upper bound of the IPCC projections, a number of authors (Rahmstorf 2007; Grinsted et al., 2009) developed relatively simple parameterisations of sea-level rise, based on the relationship between observed historical global sea-level and atmospheric surface temperature records. These semi-empirical models have generally produced higher projections than those in the IPCC AR4. While these models are an attempt to overcome the limited understanding of potential future ice-sheet contributions, the processes leading to sea-level rise are not explicitly considered but are represented by a few statistically determined parameters. The validity of these models has been questioned and there is an urgent need to evaluate their use and applicability.

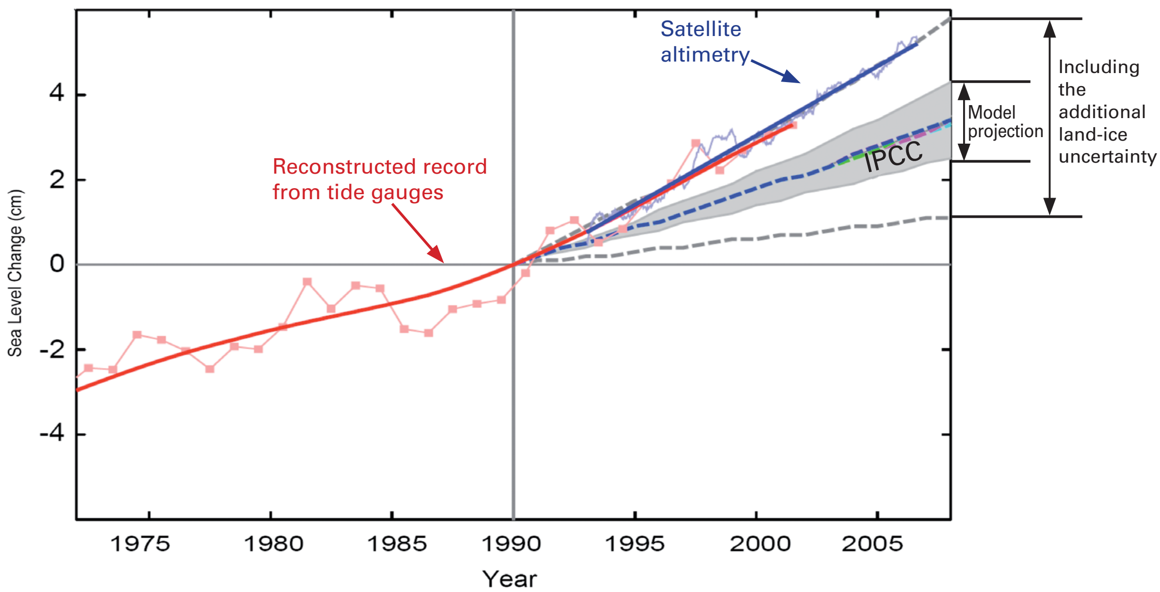


Fig. 7. Observed sea-level rise from tide gauges and satellite altimeter compared with IPCC TAR projections. Sea-level data based primarily on tide gauges (annual, red) and satellite altimeter (3-month data spacing, blue, up to mid-2006). *Based on figure from Rahmstorf et al. 2007 and http://www.pik-potsdam.de/~stefan/material/observations_vs_projections.ppt)*

SEA LEVELS WILL CONTINUE TO RISE FOR CENTURIES

Glaciers and ice caps (outside the polar regions) contain a limited amount of ice (less than about 40 cm of equivalent sea-level rise if they were all to melt), so their contribution to sea-level rise is limited. However, ocean thermal expansion will continue for centuries, even after greenhouse gas concentrations in the atmosphere have been stabilised, due to the slow transfer of heat from the surface to the deep ocean. The eventual sea-level rise would be dependent on the concentration of greenhouse gases and atmospheric temperatures; climate model simulations suggest of the order of 0.5 m per degree Celsius of global warming.

The Antarctic and Greenland Ice Sheets are the biggest concern for longer term sea-level rise. The area and mass of melt from the Greenland Ice Sheet (which contains enough water to raise sea level by about 7 m) is increasing. Model simulations indicate that surface melting of the Greenland Ice Sheet will increase more rapidly than snowfall, leading to a threshold stabilisation temperature above which there is an ongoing decay of the Greenland Ice Sheet over millennia. This threshold is estimated as a global-averaged temperature rise of just 3.1° ± 0.8°C (one standard deviation) above pre-industrial temperatures. With unmitigated emissions of greenhouse gases, the world is likely to pass this threshold during the 21st century committing the world to metres of sea-level rise, although from surface melting alone this would take centuries to millenia.

Discharge from glaciers and ice streams of the Greenland and Antarctic Ice sheets are showing signs of a dynamic response, potentially leading to a more rapid rate of rise than can occur from surface melting alone. Using kinematic constraints, Pfeffer et al. (2008) estimated that sea-level rise greater than 2 m by 2100 was physically untenable and that a more plausible estimate was about 80 cm, consistent with the upper end of the IPCC estimates and the present rate of rise. This value still requires a significant acceleration of the ice-sheet contributions.

Improved understanding of the processes responsible for ice sheet changes are urgently required to improve estimates of the rate and timing of 21st century and longer-term sea-level rise.

CHANGES IN EXTREME SEA LEVEL EVENTS

Rising sea levels have been and will continue to be felt most acutely through extreme events (periods of above average sea level). These include the many storm surges associated with intense cyclones that have resulted in major loss of life over many years in low lying nations such as Bangladesh and the 1953 and 1962 storm surges in north-west Europe. Among the most recent examples are Hurricane Katrina in New Orleans and Cyclone Nargis in Myanmar.

Analysis of 20th century sea-level extreme events indicates that coastal flooding events of a given height are now happening more frequently than at the start of the 20th century. This is primarily a response to changes in mean sea level rather than a change in the frequency or intensity of storm events.

Building on the analysis at a number of locations, it is likely that by 2100 the present day “one in one hundred years” flood could be experienced more than once a year at many locations. Also, the most severe sea-level events will be higher and thus have a greater impact.

There is continuing uncertainty as to whether global warming will lead to increased storminess. Future changes are likely to vary regionally. If polar regions warm more than the tropics, the reduction in the equator to pole temperature difference could result in fewer and weaker mid-latitude storms while high latitude storms may increase in number and intensity. The AR4 concluded that the majority of future climate models show a poleward shift in storm track position in a warming climate.

The prediction of future changes in tropical storms also has many uncertainties as their small horizontal scale requires high model resolution for study. Coupled atmosphere-ocean general circulation experiments, run with increasing greenhouse gases, project enhanced sea surface temperatures and atmospheric moisture in the tropical region. Recent results indicate fewer but more intense tropical cyclones.

SEA LEVEL AND SOCIETY – THE NEED FOR MITIGATION

Climate change mitigation will be essential if the world is to avoid the most severe impacts of sea-level rise, as might occur from ongoing ocean thermal expansion or a partial collapse of the Greenland and/or Antarctic Ice Sheets. Sea-level projections for 2100 for the highest greenhouse gas emission scenario considered in the IPCC AR4 (IPCC 2007) are about 50% larger than for the lowest emission scenario. On the longer term, ocean-thermal expansion is roughly proportional to the amount of global warming and the Greenland Ice Sheet is likely to be largely eliminated by anthropogenic climate change unless there are substantial emission reductions.

SEA LEVEL AND SOCIETY – THE NEED FOR ADAPTATION

Even with successful mitigation, adaptation to rising sea levels will be essential. During the 21st century, sea level will move substantially outside the range experienced by present day society. Where coasts are subsiding due to natural and human-induced processes, such as in many densely-populated deltas and associated cities, this effect will be exacerbated. Rising sea levels will result in a number of impacts including (1) more frequent coastal inundation, (2) ecosystem change, such as saltmarsh and mangrove loss, (3) increased erosion of beaches and soft cliffs, and (4) salinisation of surface and ground-waters. Indicative estimates suggest that about two hundred million people, and infrastructure worth one trillion dollars, are threatened by coastal floods today. This exposure continues to grow at a rapid rate, primarily due to socio-economic trends, and in the absence of adaptation, risks are growing as sea levels rise.

Appropriate adaptation can significantly reduce the impact of sea-level rise. Planned adaptation will range from retreat from rising sea levels, through planning and zoning of vulnerable coastal regions, accommodation through modification of coastal infrastructure and the construction of facilities like cyclone protection centers, to protection of highly valued coastal regions. Planned adaptation is more cost effective and less disruptive than forced adaptation in response to the impacts of extreme events and needs to be undertaken in the context of the many pressures on coastal regions as a result of rapid coastal development.

IMPROVED UNDERSTANDING IS REQUIRED TO REDUCE COSTS

The understanding of sea-level rise and variability has progressed considerably over the last decade, largely as a result of dramatically improved in situ and satellite observational systems and improved models of the climate system. However, the broad range of current projections of global averaged sea-level rise for the 21st century is primarily the result of inadequate understanding of the factors controlling the global-averaged sea-level rise and its regional distribution.

Improving observation and modeling of the global oceans, glaciers and ice caps and of the Greenland and Antarctic Ice Sheets, and detecting early signs of any growing ice sheet contributions are critical to informing decisions about the required level of greenhouse gas mitigation and adaptation planning. How much the Greenland and Antarctic Ice Sheets will contribute to sea-level rise during the 21st century and beyond is currently the largest single uncertainty.

Planning for and early warning of extreme events, through improved storm-surge modeling and its operational application, are important aspects of coastal zone management in some regions. Ensuring that nations have access to the necessary information for adaptation planning is dependent on continued progress in the implementation of observing systems, improvement of models of the climate system and local decision support tools.

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