Understanding global sea levels: past, present and future

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Abstract

The coastal zone has changed profoundly during the 20th century and as a result society is becoming increasingly vulnerable to the impact of sea-level rise and variability. This demands improved understanding to facilitate appropriate planning to minimize potential losses. With this in mind, the World Climate Research Programme organized a workshop (held June 2006) to document current understanding and to identify research and observations required to reduce current uncertainties associated with sea-level rise and variability. While sea levels have varied by over 120 m during glacial/interglacial cycles, there has been little net rise over the past several millennia until the 19th century and early 20th century when geological and tide-gauge data indicate an increase in the rate of sea-level rise. Recent satellite-altimeter data and tide-gauge data indicate sea levels are now rising at over 3 mm yr^{-1}. The major contributions to 20th and 21st century sea-level rise are thought to be a result of ocean thermal expansion and melting of glaciers and ice caps. Ice sheets are thought to have been a minor contributor to 20th century sea-level rise but are potentially the largest contributor in the longer-term. Sea levels are currently rising at the upper limit of the projections of the Third Assessment Report of the Intergovernmental Panel on Climate Change, and there is increasing concern of potentially large ice-sheet contributions during the 21st century and beyond, particularly if greenhouse gas emissions continue unabated. A suite of ongoing satellite and *in situ* observational activities need to be sustained and new activities supported. To the extent that we are able to sustain these observations, research programmes utilizing the resulting data should be able to significantly improve our understanding and narrow projections of future sea-level rise and variability.

Introduction

Coastal zones have changed profoundly during the 20th century, primarily due to growing populations and increasing urbanization and in 1990, 23% of the world's population (or 1.2 billion people) lived both within a 100 km distance and 100 m elevation of the coast at densities about three times higher than the global average (Small and Nicholls 2003). As a consequence the coastal zone and its inhabitants are becoming increasingly vulnerable to flooding and storm events, in particular against a background of rising sea level.

Sea-level rise is an important aspect of anthropogenic climate change. By 2010, 20 out of 30 mega-cities will be on the coast, with many threatened by sea-level rise (Nicholls 1995). 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 (for example Graumann et al. 2005). For projected sea-level rise during the 21st century, many millions of people will have to respond to coastal flooding events each year. With appropriate planning and adaptation measures, this number can be reduced dramatically (Nicholls et al. this volume). Rising sea levels will contribute to increased severity of storm-surge events, even if storm intensities do not increase in response to the warming of the oceans. Rising sea levels will also contribute to the recession of the world's sandy beaches, 70% of which have been retreating over the past century with less than 10% prograding (Bird 1993). Low-lying islands are also vulnerable.

An improved understanding of sea-level rise and variability will help reduce the uncertainties associated with sea-level rise projections, thus contributing to more effective coastal planning and management. Adaptation measures to minimize the potential losses include strengthened building codes, restrictions on where, what and how to build, and developing local infrastructures that is able to cope better with flooding.

There are significant uncertainties in understanding how sea level has changed on millennial to decadal time scales and what contributes to this change. As a result, there are significant uncertainties about how sea level will change in the future. To address these uncertainties, the World Climate Research Programme (WCRP) organised a workshop on Understanding Sea-level Rise and Variability. The workshop, supported by many sponsors and hosted by the Intergovernmental Oceanographic Commission at UNESCO headquarters in Paris June 6-9, 2006, brought together representatives from all relevant disciplines. In total, 163 scientists from 29 countries, including participants from developing nations and students as well as experienced research scientists and leading program managers, attended the Workshop. The goals of the Workshop were to identify 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 also conducted in support of the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan (http://earthobservations.org/docs/10-Year%20Implementation%20Plan.pdf); as such, it helped develop international and interdisciplinary scientific consensus for those observational requirements needed to address sea-level rise and its variability.

As an introduction to this volume on sea-level rise, we will draw heavily on the results from the workshop (Church et al. 2007), including the workshop's statement available at http://wcrp.wmo.int/AP_SeaLevel.html and presentations and posters at the workshop. We will briefly review historical sea-level changes, attempting to synthesise the various estimates derived from different observational methods. We also review the contributions to 20th century sea-level rise, briefly discuss the impacts of sea-level rise and the outlook for the future.

Historical sea-level rise

Sea level has varied by more than 120 m during glacial-interglacial cycles (Figure 1) as the major ice sheets formed and decayed, particularly in high northern-hemisphere latitudes (Lambeck and Chappell 2001). Paleo data indicate that sea level was 4 to 6 m (or more) above present day sea levels during the last interglacial period, about 125,000 years ago (Stirling et al. 1998; Overpeck et al. 2006). Climate and ice-sheet model simulations (Otto-Bleisner et al. 2006) indicate that Greenland was about 3° C warmer than today and that the Northern Hemisphere ice sheets contributed 2.2 to 3.4 m to the higher sea level, with the majority of the higher sea level coming from the partial melting of the Greenland ice sheet. From the last interglacial to about 20,000 years ago sea level fell by over 120 m. Following the last glacial maximum about 20,000 years ago, sea level rose by more than 120 m, at an average rate of about 10 mm yr^{-1} (1 m per century), and with peak rates of about 40 mm yr^{-1} (4 m per century), until about 7,000 years ago (Fairbanks, 1989; Lambeck et al. 2002). Sea level rose much more slowly over the past 7,000 years (Figure 1b; Lambeck 2002). Paleo data over centuries to millenia constrain estimates of sea-level change and thus of on-going ice-sheet contributions. For example, sea level about 2,000 years ago can be deduced by examining fish tanks built by the ancient Romans. Because the tanks had to be at sea level for the sluice gates to function, one can precisely estimate sea level during the period of their use. Comparison of this level with historical records (after correcting for land motion) indicates that there has been little net change in sea level from 2000 years ago until the start of the 19th century (Lambeck et al. 2004).

Changes in local sea level estimated from sediment cores collected in salt marshes reveal an increase in the rate of sea-level rise in the western and eastern Atlantic Ocean during the 19th century and early 20th century (Donelly et al. 2004; Gehrels et al. 2005; Gehrels et al. 2006), consistent with the few long tide-gauge records from Europe and North America (Woodworth 1999). Correcting these local sea-level trends for estimates of large-scale vertical land motion associated with changing surface loads on the earth (GIA, glacial isostatic adjustment) results in rates of sea-level rise close to zero in the early part of the sedimentary record and in good agreement with the tide-gauge data for the latter part of the record. Plotting these early trends as zero (Figure 2) also results in good agreement between the 20th century estimates of sea-level rise determined from the sedimentary record and from tide gauges (see below).

From 1993 to the end of 2006, near-global measurements of sea level (between 66°N and 66°S) made by high precision satellite altimeters indicate global average sea level has been rising at 3.1 ± 0.4 mm yr^{-1} (Beckley et al. 2007; Figure 3a; Unless stated otherwise, all errors estimates quoted are one standard deviation). This rate is faster (by almost a factor of two) than the average rate of rise during the 20^{th} century, which in turn was an order of magnitude larger than the rate of rise over the two millennia prior to the 18^{th} century. Church and White (2006) combined empirical orthogonal functions calculated from satellite altimeter data with coastal and island tide-gauge data (Woodworth and Player 2003), corrected for glacial isostatic adjustment (e.g. Davis and Mitrovica 1996) to estimate ('reconstruct') global average sea level. They showed that sea level rose by just under 20 cm between 1870 and 2001, at an average rate of 1.7 mm yr^{-1} during the 20^{th} century and with an increase in the rate of rise over this period (Figure 3). Jevrejeva et al. (2006) used a different technique but obtained a similar global curve. The time series of global-averaged sea level is consistent with the geological data (Figure 2), the few long records of sea level from coastal tide gauges and for the period of high-quality satellite-altimeter data since 1993 (Figure 3).

Estimates of sea-level trends during 20 year periods, with the start of each period incremented by one year, indicate significant variability in the rate of sea-level rise. Prior to the 1930s, the rate of sea-level rise was generally less than 1 mm yr^{-1} (Figure 3b). From the late 1930s to the late 1950s, the rate of sea-level rise was greater than 2 mm yr^{-1}, peaking at about 2.5 mm yr^{-1}. From 1963 to 1991 there were a series of explosive volcanic eruptions which caused cooling (and hence contraction) of the upper ocean and presumably offsetting some of the increase in sea-level rise that would otherwise have been present (Church et al. 2005; Church and White 2006; Gregory et al. 2006; Gleckler et al. 2006a and b) and the rate of sea-level rise fell to less than 2 mm yr^{-1} from the late 1950s to the mid-to-late 1980s. For the 20 year periods centred on 1992 and later, the rate of sea-level rise is close to the value estimated using satellite altimeters of over 3 mm yr^{-1}. Indeed, the rate of rise over the five most recent 20-year periods is 25% greater than the next largest set of values during the 1940s. A histogram of these rates of sea-level rise has a mean value of about 1.4 mm yr^{-1} and the five most recent values are at the extreme end of the histogram at about two standard deviations from the mean value. These results suggest that the rate of global averaged sea-level rise since the mid-1980s is indeed unusual, in agreement with Holgate and Woodworth (2004) who pointed to the anomalous 1990s rise based on tide-gauge data. Woodworth et al. (submitted) recently reviewed the evidence of changes in the rate of sea-level rise and concluded there was a strong acceleration in the early 20th century, and a weaker deceleration during the mid- to late 20th century, which Church et al. (2005) and Church and White (2006) argue is at least partly a result of explosive volcanic eruptions.

The satellite-altimeter data indicate that the rate of rise is not uniform around the globe. The spatial patterns reflect climate variability with a greater rate of rise in the western Pacific compared with the eastern Pacific as a result of the transition from El Niño-like conditions at the start of the satellite altimeter record to more La Niña-like conditions at the end of the satellite altimeter record (Figure 4a). There are also local maxima in the rate of sea-level rise at the poleward boundaries of the subtropical gyres in the South and North Pacific Ocean and in the Indian Ocean, which appear as maxima at about 40°N and 40°S in the zonal average of the rate of sea-level rise. In the southern hemisphere, this is a result of the decadal increase of the Southern Annular mode (SAM), which results in enhanced Ekman convergence and downward displacement of isopycnals at these latitudes (Roemmich et al. 2007). Over the 1950 to 2000 period, the reconstructed sea levels (Church et al. 2004) also indicate that the rate of sea-level rise is not globally uniform, but the short-term climate variability (which are clearly seen in the altimeter record), such as El Niño/La Niña and other climate variability, have a weaker impact on the multi-decadal trends (Church et al., 2004).

Impacts of sea-level rise are determined by sea-level changes relative to the local land rather than the global-average sea-level changes discussed above. Vertical land movements can occur through natural geological processes resulting in uplift or submergence, or from man-made influences, usually resulting in submergence. The process with the largest spatial scale (glacial isostatic adjustment, GIA) results from global-scale changes in mass loading of the Earth's surface as a result of the melting of ice sheets and the associated increased mass of the oceans. Today, there are ongoing viscoelastic changes in the solid earth as a result of the changing loads of the ice sheets during the last glacial/interglacial cycle (Lambeck and Nakiboglu 1984; Peltier 1998) and the present day elastic response to recent melting (Mitrovica et al. 2001). In addition to these large-scale motions, there are local tectonic motions. In a number of deltaic regions with high population densities, ground water withdrawal, oil and gas extraction, compacting sediments and reduced supply of new sediments as a result of dam building and altered river flows (Ericson et al. 2006) results in significant subsidence rates, further exacerbating the impact of sea-level rise.

Contributions to 20th century sea-level rise

The two main reasons for sea-level rise are thermal expansion of ocean waters as they warm, and increase in the ocean mass, principally from land-based sources of ice (glaciers and ice caps, and the ice sheets of Greenland and Antarctica). Global warming from increasing greenhouse gas concentrations is a significant driver of both contributions to sea-level rise.

Ocean-thermal expansion

For the 1993 to 2003 period, a variety of analysis techniques have been used to estimate the rate of global-averaged and regional ocean-thermal expansion. The results of Antonov et al. (2005) and Ishii et al. (2006) indicate a rate of ocean thermal expansion of about 1.2 mm yr^{-1}. A number of studies have shown that altimetric sea-level heights are highly correlated with heat content and steric heights (White and Tai, 1995, Gilson *et al.*, 1998, Willis *et al.*, 2003, 2004). This correlation can be exploited to improve estimates of ocean thermal expansion and heat content (0-750 m) as shown by Willis et al. (2004). The altimetric height correlation with subsurface temperature was used to form a first guess of the heat-content (or thermosteric height) variability, and then anomalies from this first guess were objectively mapped using the subsurface data. The resultant estimate of ocean thermal expansion for 1993 to 2003 (Willis *et al.* 2004) was 1.6 mm yr^{-1}.

An alternative approach to fill the gaps in the sparse *in situ* data base is a reconstruction of ocean thermal expansion based on empirical orthogonal functions in an approach similar to that used by Church et al. (2004) to estimate changes in sea level (Domingues et al. submitted).

While these and other estimates have similar rates averaged over 1993-2003, there are significant interannual differences between the estimates and all are strongly dependent on eXpendable-Bathy-Thermograph (XBT) data. When the recent Argo data was added to this time series there was an apparent ocean cooling since 2003 (Lyman et al. 2006), which has since been shown to be the result of a time-variable warm bias in the XBT data, resulting in too large an estimate of thermal expansion from 1993 to 2003, and errors in the Argo data (Willis et al. 2007), resulting in unrealistic estimates of ocean cooling since 2003. Wijffels et al. (2008) has recently shown that the significant XBT warm biases identified by Gouretski and Koltermann (2007) are primarily a result of errors in the XBT fall rate which varies over decades (presumably as a result of small changes in the manufacture of the XBTs). Revised estimates of ocean thermal expansion for the upper 700 m are currently being computed and are likely to be lower than earlier estimates; revised estimates may be a little less than 1 mm yr^{-1} for 1993 to 2003.

The regional distribution of sea-level variability and rise is largely a result of the regional distribution of ocean thermal expansion. As a result, the spatial pattern of trends (relative to their respective global means) of sea-level rise measured by satellite altimeter (Figure 4a) and ocean thermal-expansion computed using a reduced space optimal interpolation technique (Figure 4b; Domingues et al. submitted) are very similar. In constructing Figure 4b, spatial empirical orthogonal functions (EOFs) computed from altimeter data were used but similar results are found when EOFs computed from the dynamic height data of Guinehut et al. (2006) are used.

From 1955 to 2003, Antonov et al. (2005) estimated ocean thermal expansion over the upper 700 m contributed about 0.3 mm yr^{-1} to sea-level rise and 0.4 mm yr^{-1} over 3000 m, less than 25% of the observed rise over the same period. However, there are significant XBT biases in the data set and there are major gaps in the data base. The estimated rate of thermal expansion is sensitive to how these data gaps are filled (see also AchutaRao et al. 2007). A reconstruction of ocean thermal expansion based on empirical orthogonal functions using the XBT fall rate corrections of Wijffels et al. (2008) results in a somewhat larger value than earlier estimates (Domingues et al. submitted), about 0.5 mm yr^{-1} for the upper 700 m for 1960 to 2003. Gille (2008) found a similar sensitivity to gaps in the observational data base in the Southern Ocean and concluded that the previous results (Antonov et al. 2005) were biased low.

Glaciers and ice caps

Glaciers and ice caps (i.e. excluding the Greenland and Antarctic ice sheets) together contain enough water to raise sea level by between 15 and 37 cm (Lemke et al. 2007). Despite their size, they are thought to be the second largest contributor to sea-level rise during the 20th century, and are likely to be the second largest during at least the early 21st century (Meier et al. 2007). Kaser et al. (2006) summarise recent estimates of the contribution of the melting of glaciers and ice caps to sea-level rise. Including the smaller glaciers surrounding Greenland and Antarctica, they estimate a contribution to sea-level rise of about 0.4 mm yr^{-1} from 1961 to 1990 increasing to about 1.0 mm yr^{-1} from 2001-2004. The most important impact is from large glaciers in regions with heavy precipitation, such as the coastal mountains around the Gulf of Alaska, Patagonia and Tierra del Fuego in South America. The time-series from Dyurgerov and Meier (2005, our Figure 5) is typical of the estimates and shows the increasing contribution of glaciers and ice caps since 1960. Lemke et al. (2007) conclude that the glacier wastage is likely to have been a response to post-1970 warming. One of the estimates summarized by Kaser et al., that of Cogley (2005), shows a larger contribution to sea-level rise in the 1940s (but with larger error bars) at the same time as global averaged sea level is estimated to be rising relatively rapidly (Figure 3).

The Ice Sheets of Greenland and Antarctica

The ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty. At the time of the Third Assessment Report (TAR) of the IPCC (Church et al. 2001), direct observational estimates of the balance of the Greenland and Antarctic ice sheets were too imprecise to be of value in assessing the global sea-level budget. Instead, the TAR relied on models to estimate that the ice sheets could be contributing anywhere between zero and 0.5 mm yr^{-1} to 20^{th} century sea-level rise. Since 1990, there has been a rapid increase in the quantity and quality of remote sensing data available for estimating changes in the mass of both ice sheets. For Greenland, new estimates depend on the use of airborne laser altimeters, satellite altimeters (Krabill et al. 2004; Thomas et al., 2006), synthetic aperture radar (Rignot and Kangaratnam, 2006) and most recently time variable gravity measurements (Velicogna and Wahr 2005; Ramillien et al. 2006; Luthcke et al. 2006; Chen et al. 2006).

Since 1990 there has been increased snow accumulation at high elevation on the Greenland ice sheet (Zwally et al. 2005), while at lower elevation there has been more widespread surface melting and a significant increase in the flow of outlet glaciers (Rignot and Kanagaratnam, 2006). The net result is a decrease in the mass of the Greenland ice sheet — a positive contribution to sea-level rise of perhaps 0.2 ± 0.1 mm yr^{-1} (90% confidence range; Lemke et al. 2007) — and suggestions of an acceleration of this contribution (Rignot and Kanagaratnam, 2006; Chen et al. 2006). However, the time series are short and the estimates may not be representative of longer periods and of the twentieth century as a whole.

For the Antarctic Ice Sheet, the uncertainty is even larger. As temperatures increase, snowfall is projected to increase, partially offsetting other contributions to sea-level rise.

However, no significant increase in snowfall has been detected over the last 50 years (Monaghan et al. 2006). The West Antarctic Ice Sheet is grounded below sea-level and warm ocean water can penetrate beneath the fringing ice shelves, melting the ice sheet at its base and leading to increased flow of outlet glaciers (Thomas et al. 2004), as observed on the Antarctic Peninsular following the collapse of the Larsen B Ice Shelf (Scambos et al. 2004; Rignot et al. 2004). However, those processes are poorly understood and thus not adequately modelled. Since 1993, moderate increases in ice thickness in East Antarctica (Zwally et al. 2005; Davis et al. 2005) do not appear to compensate for the mass loss due to the increased glacier flow on the Antarctic Peninsula and the West Antarctic Ice Sheet (Zwally et al. 2005; Davis et al., 2005; Joughin et al. 2003; Thomas et al. 2004). The net result is estimated to be a contribution to sea-level rise of 0.2 ± 0.4 mm yr^{-1} (90% confidence range; Lemke et al. 2007). Note also that modelling studies (e.g. Huybrechts and de Wolde 1999) argue that because of the very long response time of ice sheets, the Antarctic Ice Sheet is still responding to changes since the last ice age and thus contributing to present day sea-level rise.

Changes in Terrestrial storage

As part of the hydrological cycle, water is exchanged between the oceans and "reservoirs" on land (lakes, rivers, soil moisture, groundwater, ice sheets, permafrost). Natural (e.g. El Niño, volcanic eruptions), man-made (e.g. dams, irrigation) and climate-driven changes to precipitation, evaporation, soil moisture and glaciers and ice caps affect this cycle.

The largest terrestrial storage changes arising from climate variations on interannual to decadal scales are a result of changes in groundwater storage, followed by changes in soil moisture and then snow cover (Ngo-duc et al. 2005; Milly et al. 2003). Ngo-duc et al. (2005) found that during the 1970s about 4 mm (equivalent sea level) more than normal was held in terrestrial storage, but over the 50 year period 1950 to 2000 there was little net change. For the period since the early 1990s, a range of terrestrial water models have been inter-compared and GRACE gravity data is also being used to test these models and to directly estimate changes in terrestrial water storage.

As well as these climate-driven changes in terrestrial water storage, human activities also affect terrestrial storage and sea level. These activities include mining of groundwater, deforestation, desertification, wetland loss or drainage, surface water diversion and dam building. However, the sum of these terms is poorly known. The contribution from sedimentation in the ocean is small (Church et al., 2001).

Reducing Uncertainties

Improving our understanding of sea-level rise and variability, as well as reducing the associated uncertainties, depends critically on the availability of adequate observations. The WCRP workshop (http://wcrp.ipsl.jussieu.fr/Workshops/SeaLevel/), helped develop international scientific consensus for those observational requirements needed to address sea-level rise and its variability. These requirements include sustaining existing systematic observations, as well as the development of new and improved observing systems.

An overarching observational requirement is the need for an open data policy, together with timely, unrestricted access for all. Using the Argo and Jason policies (http://www.coriolis.eu.org/cdc/argo/argo_data_management_handbook.pdf and http://podaac-www.jpl.nasa.gov/about/) as a guide, this access would include real-time, high-frequency sea-level data from the GLOSS tide gauges and co-located GPS stations, as well as data from satellite missions and *in situ* observing systems. Further requirements include the need for appropriate data archaeology—retrieving and making accessible historical, paper-based sea-level records, especially those extending over long periods and in the Southern Hemisphere. An immediate priority for paper records is electronic scanning and making them available for subsequent digitization. Moreover, satellite observations need to be as continuous as possible, with overlap between successive missions. There also needs to be a corresponding collection of appropriate *in situ* observations for calibration and validation. Ongoing satellite and *in situ* observing systems should adhere to the Global Climate Observing System (GCOS) observing principles (http://gosic.org/GCOS/GCOS climate_monitoring_principles.htm).

The existing systems that should be sustained include those observing sea level – the Jason series of satellite altimeters, as well as completing the GLOSS network of approximately 300 gauges (each with high-frequency sampling, real-time reporting, and geodetic positioning). In order to estimate the change in sea level due to steric effects, the Argo array – which achieved global coverage of the ice-free oceans with 3,000 profiling floats in November 2007 – needs to be sustained. To estimate the change in sea level due to changes in ocean mass due to melting ice caps and glaciers and changes in terrestrial water storage, observations of the time-varying gravity field from GRACE need to be sustained.

Additional existing systems to be sustained are those required to observe changes in ice sheet and glacier topography and thickness: satellites utilizing radar (e.g., Envisat, GFO and Sentinel-3) and laser (ICESat and, once launched, CryoSat-2) altimeters, complemented by aircraft and *in situ* observations. All of these measurements require that the International Terrestrial Reference Frame (ITRF), which integrates the geodetic components – SLR, VLBI, DORIS, and GNSS (GPS, together with GLONASS & Galileo once launched), must be made more robust and stable than is currently the case. Finally, higher spatial resolutions observations from GOCE, once launched, and other stand-alone missions are needed to obtain improved models of the planetary gravity field, including its temporal variation, such that we can separate changes in sea-surface shape, which reflect mass redistribution and density changes from changes in the geopotential which reflect the mass distribution only.

New and improved observing systems which need to be developed include those directed at changes in the ocean volume, specifically extending the Argo-type capability to enable the collection of similar observations under the sea ice, as well as the design and implementation of an effort to obtain observations for the deep ocean. Based on experience gained with radar and laser satellite altimeters, the development of a suitable follow-on capability is needed to improve observations of ice sheet and glacier topography. Access to InSAR data and ongoing InSAR missions are needed to observe flow rates in glaciers and ice sheets. Finally, the development of an advanced wide-swath altimeter is needed to observe:

- sea level associated with the oceanic mesoscale field, coastal variability, and marine geoid/bathymetry,
- surface water levels on land (Alsdorf et al. 2007) and their changes in space and time and
- surface topography of glaciers and ice sheets.

The Impacts of sea-level rise

Relative sea-level rise has a wide range of effects on coastal systems. The immediate effect is submergence and increased flooding of coastal land, particularly during extreme events, as well as saltwater intrusion into surface and ground waters. In the Bay of Bengal, there have been 23 surge events with over 10,000 people killed in each since 1737 (Murty et al. 1986; Murty and Flather 1994). The most severe impacts were felt in 1737 (300,000 people killed), 1864 (100,000 people killed), 1876 (100,000 people killed), 1897 (175,000 people killed), 1970 (300,000 people killed) and 1991 (about 140,000 killed and 10 million made homeless).

In Europe the storm surge of 1953 had a major impact with the loss of over 1800 lives in the Netherlands and 300 in southeast England (Wolf and Flather 2005). This event resulted in major programmes of coastal protection in both countries. The most well-known recent example of coastal flooding is that from Hurricane Katrina in New Orleans in August 2005. This can be considered as a combined impact in which unprecedented storm-surge levels were compounded by land subsidence, as occurs naturally in all major deltas, together with anthropogenic changes such as oil withdrawal, modification to the delta wetlands, restriction of river flow, development on flood plains, sea-level rise and the failures of coastal defences. As of August 2006, estimates are that in excess of 1800 people lost their lives and there was in excess of $125 billion dollars of damage (for example Graumann et al. 2005). Many of the environmental refugees from Hurricane Katrina have not yet returned to New Orleans.

Increases in the frequency of extreme sea levels of a given height have been observed in a number of locations around the world, particularly in the Pacific Ocean and along the east coast of North America (Woodworth and Blackman 2004). Most of these increases in the frequency of extreme sea levels have occurred as a result of rising mean sea level rather than an increase in the intensity of storm surges. Data from Australia's east (Sydney) and west (Fremantle) coasts indicates that high sea levels of a given value are occurring about three times as often in the last half of the 20^{th} century compared with the first half of the 20^{th} century (Church et al. 2006). However, to date no study has revealed any significant and widespread increase in the intensity of storm surges as would be expected from the increased number of intense hurricanes (Webster et al. 2005; Emanuel 2005).

Impacts of sea-level rise are determined by the relative sea-level change, reflecting not only the global-mean trend in sea level, but also regional and local variations in sea-level change and in geological uplift and subsidence. Areas that are subsiding are more threatened. The most significant impacts may be associated with the combined impact of changes in interannual variability and extreme sea levels resulting from storms and the global averaged sea-level rise. Extreme sea-level scenarios due to changing storm characteristics need to be considered along with sea-level rise scenarios, although this information is presently much less developed for most coastal areas. As noted above, many coastal megacities are built on deltaic regions where significant sinking has occurred or is occurring (Nicholls 1995).

Deltaic regions suffer from a combination of existing anthropogenic problems (e.g. sediment entrapment by upstream dams, leading to a lack of fluvial accretion) and sea-level rise. Ericson et al. (2006) estimate that the "effective sea-level rise" (i.e. including the effect of subsidence) for 40 deltas worldwide will potentially impact 8,710,000 people by 2050, assuming a global sea-level rise of 2 mm yr^{-1} (about 2/3rds of the current rate). This figure includes 3,430,000 people in the Bengal, and 1,910,000 in the Mekong delta. These estimates do not take account of increased exposure to storm surges.

Longer-term effects also occur. These include increased coastal erosion (as mentioned above, 70% of the world's beaches have been eroding over the 20^{th} century and less than 10% prograding), ecosystem changes, and saltwater intrusion into groundwater. On sandy coastlines, beach erosion commonly occurs at tens to hundreds of times the rate of sea-level rise and will degrade or remove protective coastal features such as sand dunes and vegetation, further increasing the risk of coastal flooding.

Outlook for the Future

Projections of 21st century sea-level rise

The Intergovernmental Panel on Climate Change (IPCC) provides the most authoritative information on projected sea-level change. The IPCC Third Assessment Report (TAR) of 2001 (Church et al. 2001) projected a global averaged sea-level rise of between 20 and 70 cm between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios and a range of climate models. When an additional uncertainty for land-ice changes was included, the full range of projected sea-level rise was 9 to 88 cm. For the IPCC's Fourth Assessment Report (AR4; Meehl et al. 2007), the range of sea-level projections, using a larger range of models, is 18 to 59 cm (90% confidence limits) over the period from 1980-1999 to 2090-2099 (Meehl et al. 2007). The largest contribution is from ocean thermal expansion (10-41 cm) with the next largest contribution from glaciers and ice caps (7-17 cm). Recently, Meier et al. (2007) suggested a larger glacier and ice cap contribution of 10 to 25 cm for the 21st century. Meier et al.'s projections are based on assuming the present contribution remains steady (with no acceleration) or that the present contribution increases, with no allowance for the decreasing area and mass of glaciers and ice caps.

In the IPCC AR4 projections, the sum of the ice sheet contributions is small, partly as a result of increased accumulation on the Antarctic Ice Sheet offsetting positive contributions from elsewhere.

However, there is increasing concern about the stability of ice sheets. For Greenland, this concern is based on measurements indicating an increasing contribution from the ice sheet (e.g. Rignot and Kanagaratnam 2006), observations of melt water flowing into moulins and possibly finding its way to the base of the ice sheet, rapid sliding of glaciers at the start of the summer melt season (Zwally et al. 2002) and an increase in the frequency of ice quakes (Ekstrom et al. 2006). Much of the West Antarctic Ice Sheet is grounded below sea level and the penetration of warmer water beneath the ice shelves to the base of the ice sheet and the subsequent dynamic response is the main reason for concern. This concern has been reinforced by the acceleration of glaciers on the Antarctic Peninsula following the collapse of the Larsen B Ice Shelf (Scambos et al. 2004; Rignot et al. 2004). The current suite of ice sheet models do not adequately represent many of these processes and thus the TAR and AR4 projections of ice sheet contributions to both 21st century and longer term sea-level rise may be underestimated. Recognizing this deficiency, the IPCC AR4 increased the upper limit of the projected sea-level rise by 10 to 20 cm above that projected by the models implying a range of projected sea-level rise of 18 cm to 79 cm. It is unclear what confidence intervals to ascribe to this range given the ice sheet uncertainties. In particular, the IPCC AR4 noted 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."

While the 2001 and 2007 IPCC projections are somewhat different in how they treat ice sheet uncertainties and the confidence limits quoted, a comparison of the projections (Figure 6) shows the end results are somewhat similar, except that the lower limit of the 2001 projections has been raised from 9 cm in the TAR to 18 cm in the AR4.

Despite the additional allowance for ice sheet uncertainties, a number of scientists remain concerned that the ice-sheet contributions may have been underestimated. Rahmstorf (2007) developed a simple statistical model that related 20th century surface temperature change to 20th century sea-level change. Using this relationship and projected surface temperature increases, he estimated that 21st century sea-level rise might exceed the IPCC projections and be as much as 1.4 m. However, Holgate et al. (2007) emphasised that Rahmstorf's model is simple and may not adequately represent future change.

The concern that the sea-level projections may be biased low has been reinforced by a comparison of observed and projected sea-level rise from 1990 to the present. For this period, observed sea level has been rising more rapidly than the central range of the IPCC (2001 and 2007) model projections and is at the very upper end of the IPCC TAR projections (Figure 6; Rahmstorf et al. 2007), indicating that one or more of the model contributions to sea-level rise may be underestimated.

Longer-term implications

Irrespective of uncertainties in the particular dynamic responses of either or both ice sheets, there is no doubt that there is a surface warming value for the Greenland ice sheets above which surface melting exceeds precipitation. This value is estimated to be about 4.5 ± 0.9°C over Greenland, corresponding to a global averaged warming of about 3.1 ± 0.8°C, both compared to pre-industrial values (Gregory and Huybrechts 2006). For sustained warming above this value, there is likely to be an ongoing wastage of the Greenland ice sheet, leading to significant rise in global average sea level of up to several metres. The time scale over which this could occur is disputed. The processes included in the present generation of ice-sheet models lead to time scales of a millennium or two (Huybrechts and de Wolde 1999) whereas others (Rignot and Kanagaratnam 2006; Hansen 2007) have emphasised these fast dynamic responses of the Greenland and West Antarctic Ice Sheets implying a sea-level rise of over a metre from ice sheets alone during the 21st century.

Ocean thermal expansion will continue for centuries after greenhouse gas concentration are stabilised (Meehl et al. 2005; Wigley 2005) and could eventually be several metres, depending on future greenhouse gas concentrations. Glacier and ice cap wastage will also continue. However, melting of glaciers, particularly those at lower altitude and latitude, will eventually result in significant reduction of the sizes of the glaciers and reductions in their contribution to the rate of sea-level rise. The long-term contribution to sea level from glaciers and ice caps is limited to less than about 37 cm, the upper limit of current estimates of glacier and ice cap volume. Note however that there are significant implications for local water supply from long term melting of glaciers and ice caps for a number of regions, notably those downstream of the Himalayas and the tropical Andes.

Conclusions

Geological data indicate that there was an increase in the rate of sea-level rise in the late 19^{th} and/or early 20^{th} century and that sea level rose during the 20^{th} century at a much faster rate than the last few centuries and millennia (Figure 7). *In situ* and satellite data indicate an increase in the rate of rise since 1870 and that sea level is currently rising at a faster rate than at any time during the last 130 years. Sea level is projected to continue to rise at an increasing rate during the 21^{st} century. Even if we stabilise atmospheric concentrations at today's (or some other) level, some further increase in sea-level rise will still occur (Meehl et al. 2005; Wigley 2005; Wigley 1995).

The 20^{th} and particularly the 21^{st} centuries' sea levels are significantly higher than that experienced over recent centuries (Figure 7) and millennia (Figure 1). Significant further work is required to understand adequately 20^{th} century sea-level rise and thus improve projections for the future; a fundamental aspect of that work is the need to sustain and enhance a suite of ongoing satellite and *in situ* observing systems.

For the period 1961 to 2003, the sea-level budget is not closed – sea level was rising at 1.8 mm yr^{-1}, faster than estimated from knowledge of the contributions at about 1.1 mm

yr^{-1} (Bindoff et al. 2007). For 1993-2003, Bindoff et al. report that the sum of the contributions was approximately equal to the observed rise. However, it is now known that the thermal expansion was over-estimated for this period. Closing the sea-level budget is an area of active research. Over the last several decades, including the period of the IPCC projections since 1990, models indicate a slower rate of sea-level rise than observed, thus raising concern about the adequacy of projections for the 21st century. This observation and the uncertainty about ice-sheet stability, for example as raised by Hansen (2007), further raises concern about the magnitude and the impacts of future sea-level rise.

There are significant regional variations in the rate of sea-level rise, some of which are associated with interannual climate variability. However, there are also emerging spatial patterns which may be part of a long-term trend. The current generation of climate models does not yet provide robust projections of regional patterns of sea-level rise. As a result, the global averaged sea-level rise should be considered for planning purposes, with some allowance for a potentially larger contribution as a result of the regional pattern of sea-level rise.

The impacts of sea-level rise are being felt now, they will be felt during the 21st century and in the longer term and society will need to adapt to the effects of these rising sea levels. These 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 extreme sea-level events and there will only be an increase in their numbers as a result of sea-level rise during the 21^{st} century and beyond. Adaptation requires local and regional planning to avoid the impacts of the most severe events.

There is a need to urgently reduce emissions of greenhouse gases if we are to avoid the most extreme sea-level rise scenarios. A major question is whether we will pass a critical point during the 21^{st} century that will lead to an ongoing and possibly irretrievable melting of the Greenland or West Antarctic ice sheet and a sea-level rise of several 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 millennia.

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 21^{st} century. Appropriate strategies can lead to a significant amelioration of the impacts of sea-level rise through both mitigation of our emissions and also plans to adapt to the inevitable consequences of sea-level rise.

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Acronyms

CryoSat-2 Second Cryospheric Satellite
GCOS Global Climate Observing System
GFO GeoSat Follow-On Satellite
GLONASS Global Orbiting Navigation Satellite System
GLOSS Global Sea Level Observing System
GNSS Global Navigation Satellite System
GOCE Gravity Field and Steady-State Ocean Circulation Explorer Satellite
GPS Global Positioning System
GRACE Gravity Recovery and Climate Experiment Satellite
ICESat Ice, Cloud, and Land Elevation Satellite
InSAR Interferometric Synthetic Aperture Radar
SLR Satellite Laser Ranging

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Figure Captions:

Figure 1. Estimates of sea-level change over the last 140 thousand years (Lambeck and Chappell 2001; Lambeck et al. 2002). The error bars indicate the limits of estimates from available data and the red box in (a) indicates the period covered in (b).

Figure 2. Sea-level estimates from sedimentary records near New York (Donelly et al. 2004) and Halifax (Gerhels et al. 2006) compared with the estimates of global mean sea level shown in Figure 3. The sedimentary estimates of sea level have been plotted with zero trend for the early part of the record. The estimated local sea level (compared with present day local sea level and corrected for GIA) in ancient Roman times (Lambeck et al. 2004), near the start of the tide gauge record at Amsterdam and Liverpool (Woodworth 1999) and at the Port Arthur (Tasmania, Australia) benchmark in 1840 (Hunter et al. 2003) are shown in red, brown, light blue and dark blue respectively. The error bars on these estimates are one standard deviation.

Figure 3. Global mean sea level from (a) 1870 to 2006 with one standard deviation error estimates. (b) The linear trends in sea level over 20 year periods, with one sigma error on the trend estimates shown by the dotted lines. (c) The histogram of trends over the period 1870 to 2006. The mean value and one standard deviation are shown. The values for the last five 20 year periods centred on 1992 or later are shown in red on panels (b) and (c). (T/P + J-1 is the combined TOPEX/POSEIDON and Jason-1 satellite altimeter record.)

Figure 4. The spatial distribution of the rates of sea-level rise, plotted about the mean value for the period January 1993 to December 2003, (a) as measured from satellite altimeter data, (b) the thermal expansion component for the upper 700 m as estimated from a reduced space optimal interpolation using the techniques employed by Domingues et al. (submitted).

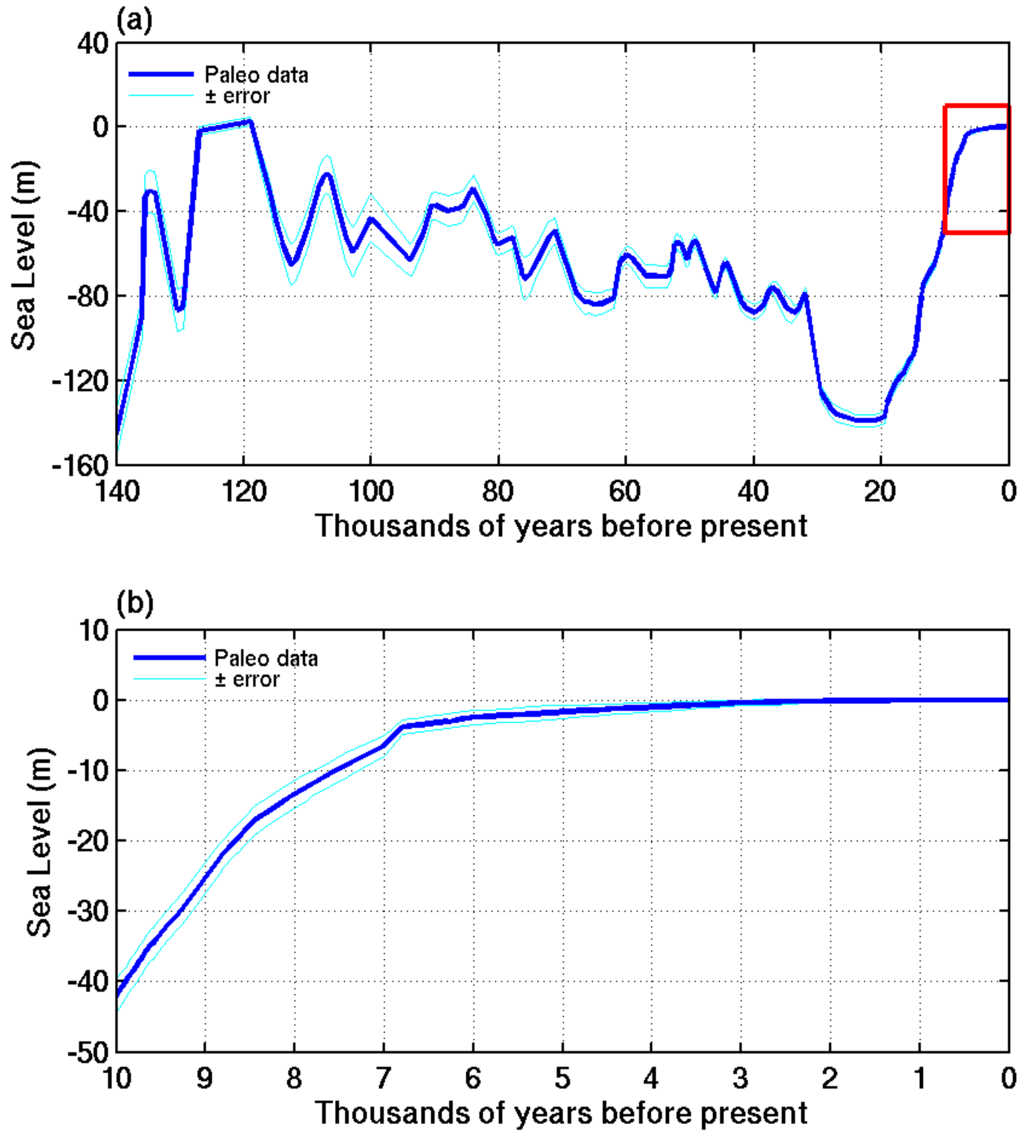
Figure 5. Contributions from glaciers and ice caps to global-mean sea level (Dyuregerov and Meier, 2005). The lower panel is the annual contribution and the upper panel is the accumulated contribution from 1961.

Figure 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 to 2100 is shown by the lines and shading. (The dark shading is the model average envelope for all SRES greenhouse gas scenarios, the light shading is the envelope for all models and all SRES Scenarios and the outer lines include an allowance for an additional land-ice uncertainty.) The updated 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. Note that the IPCC AR4 states 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." The inset

shows the 2001 projection compared with the observed rate estimated from tide gauges (blue) and satellite altimeters (orange). (Based on Church et al. 2001, Meehl et al. 2007 and Rahmstorf et al. 2007.)

Figure 7. Sea levels from 1500 to 2100. The blue bar indicates the range of paleo observations from Figure 1, 2 and 3, the dotted lines from 1700 to1860 indicate the range of sea levels inferred from the Europe's longest tide-gauge records at Amsterdam and Liverpool from Figure 2, the dark line from 1870 to 2006 indicates the global average sea level from Figure 3 and the curves from 1990 to 2100 the projections from Figure 6.

Figures



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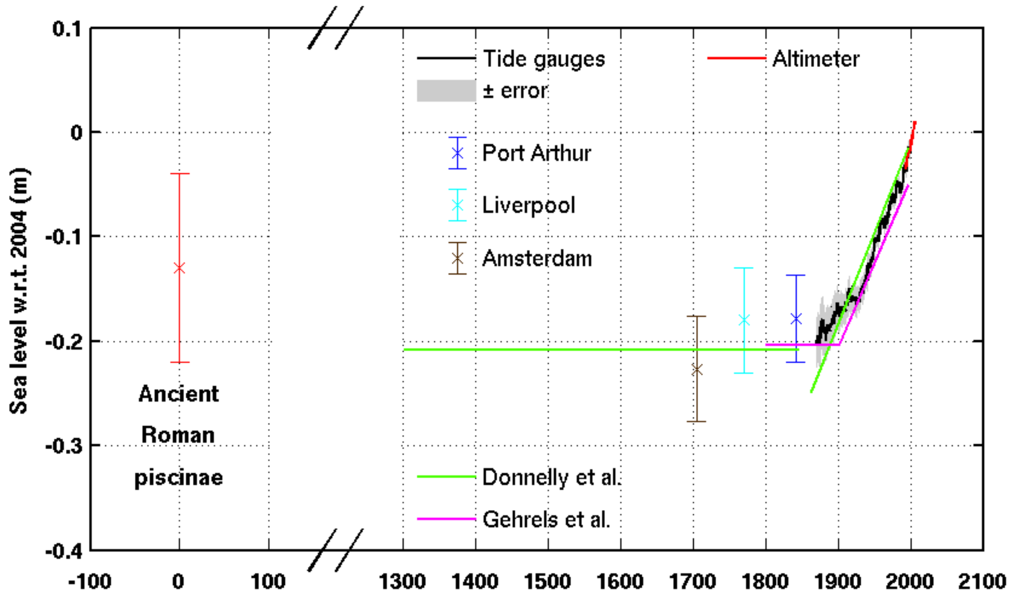

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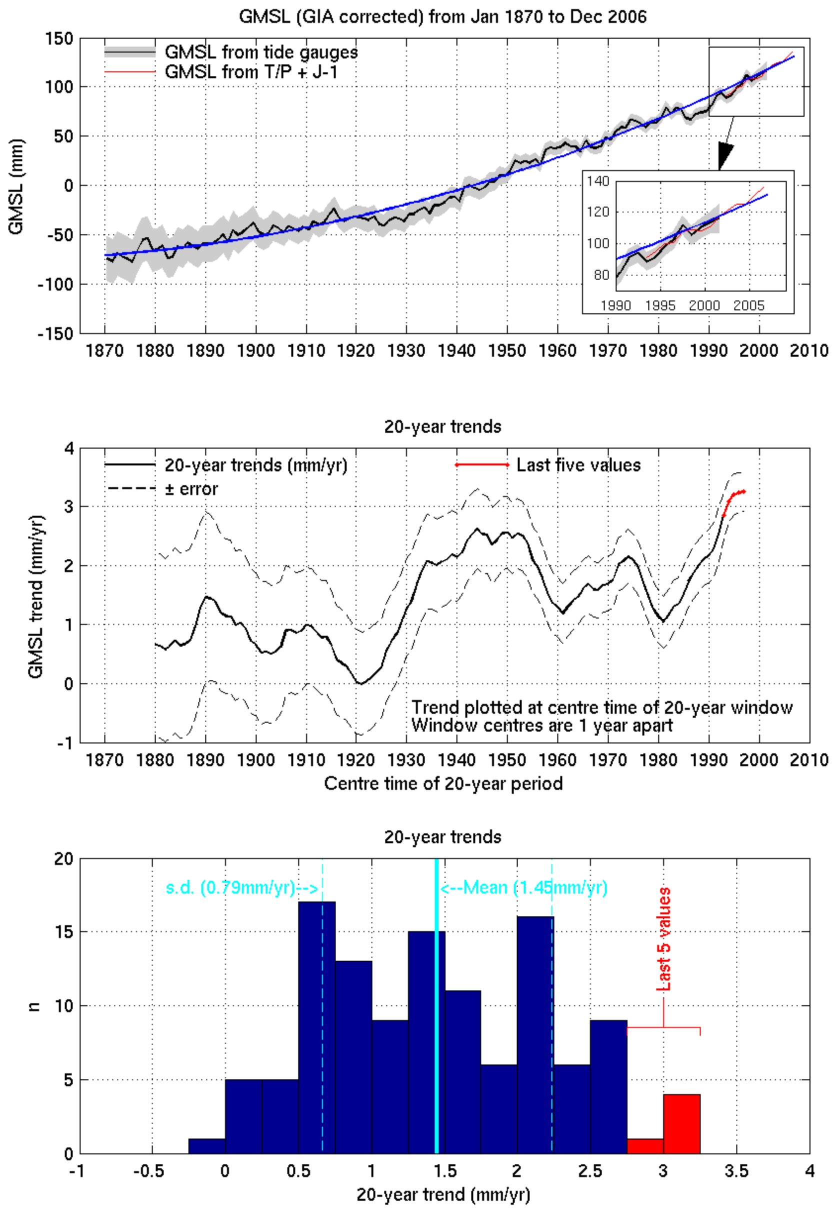

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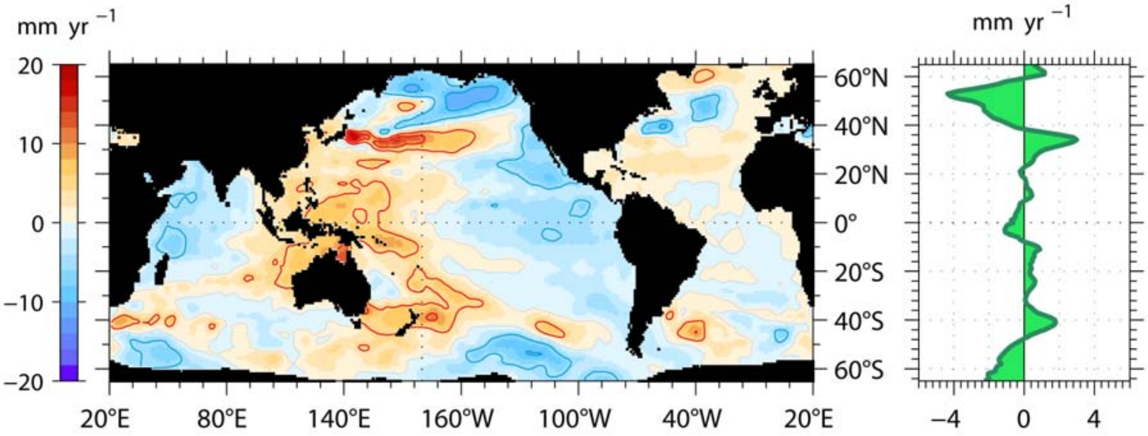

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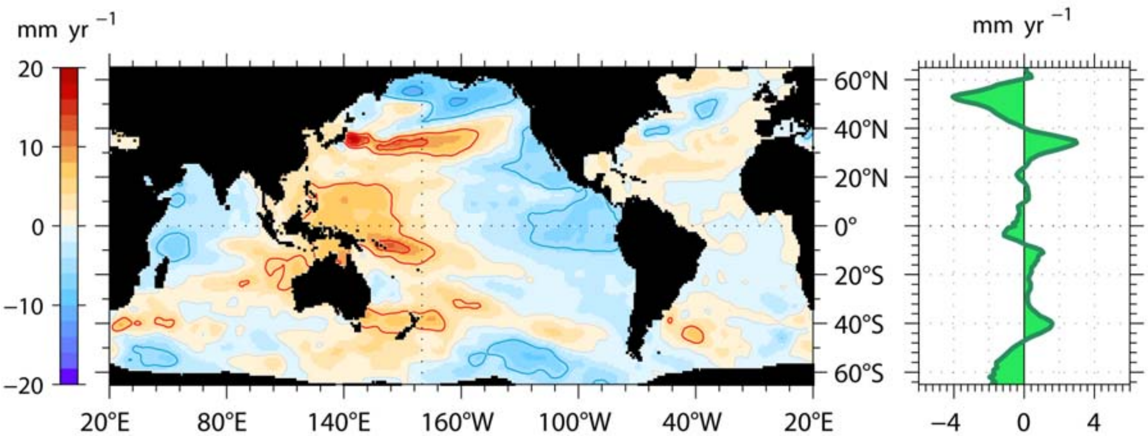

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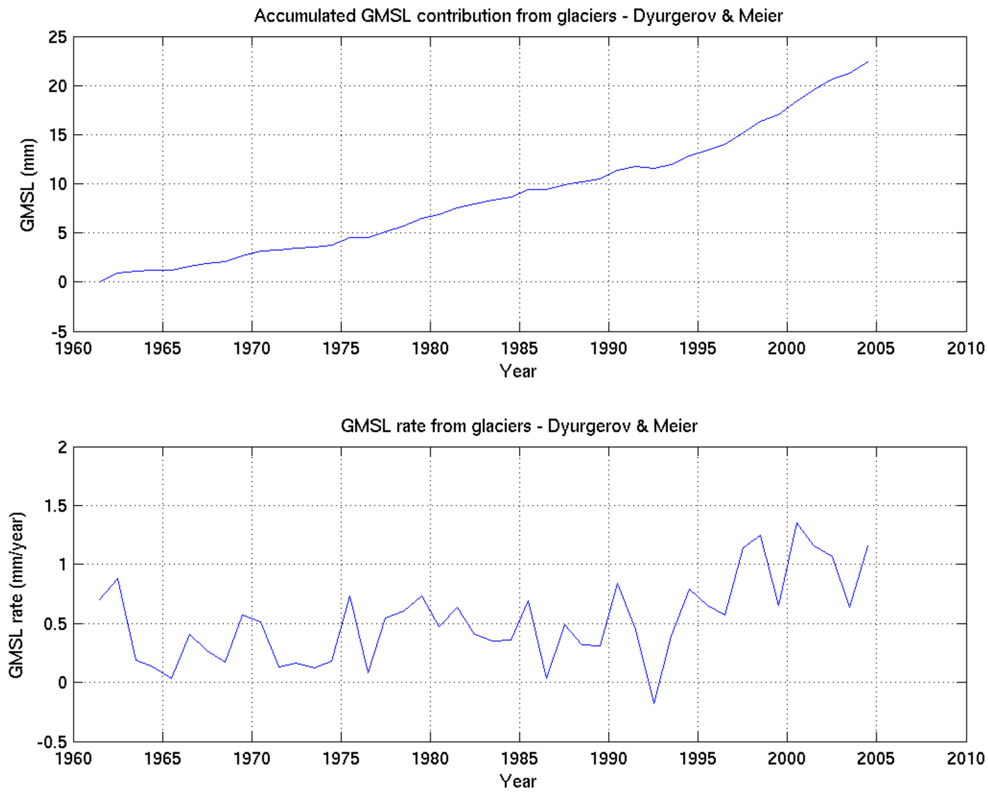

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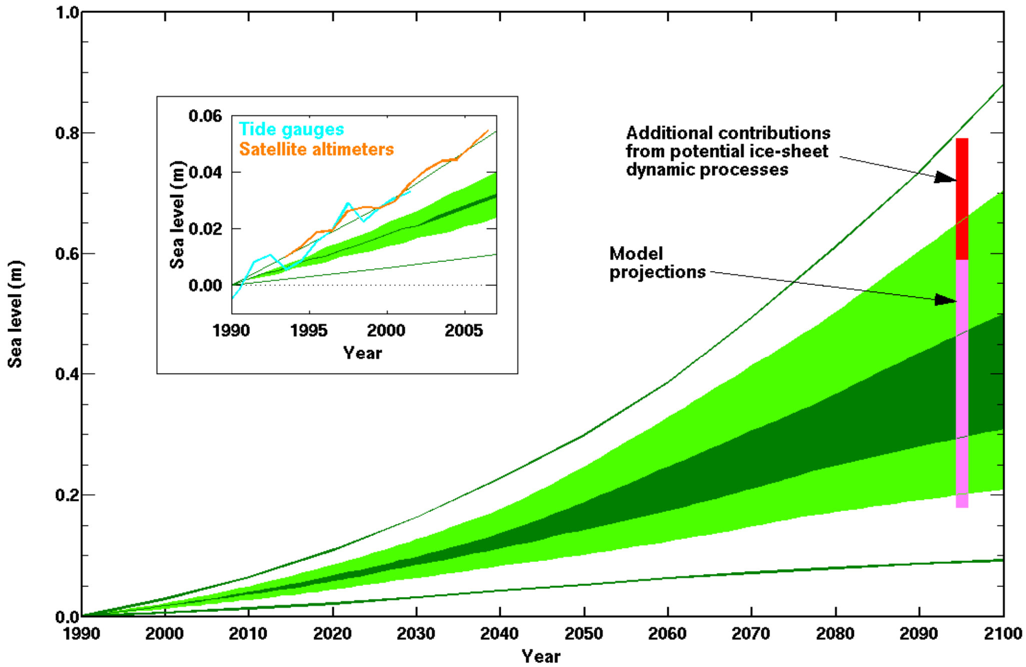

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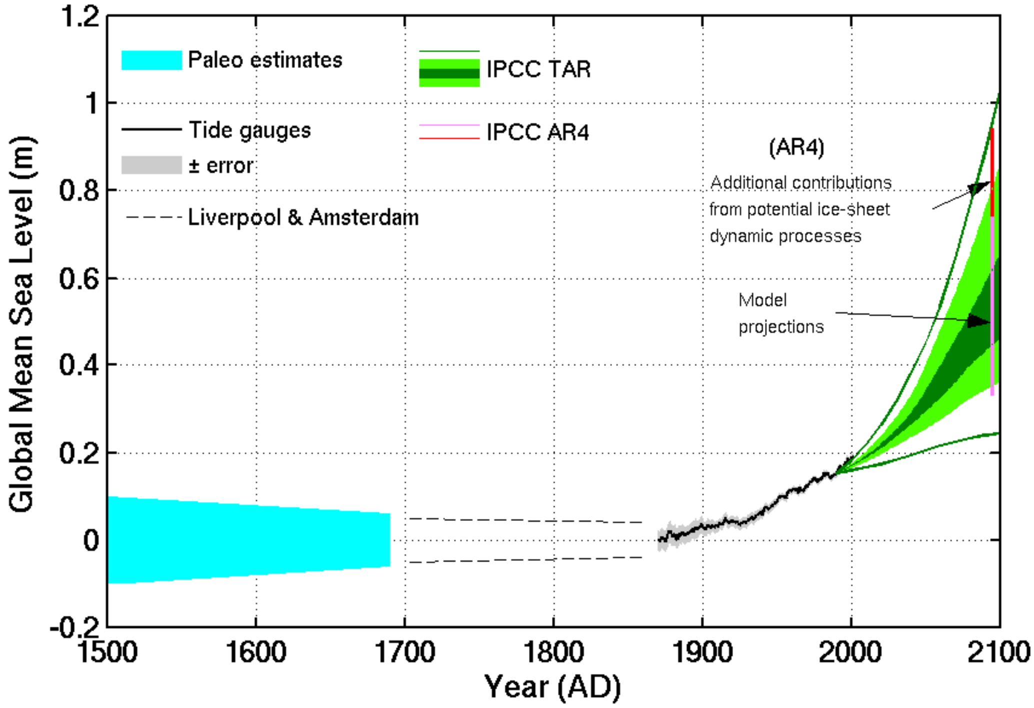

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