

# Chapter 10

## Sea Level Rise

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**Abstract** Sea level rise in the twentieth century was 1.7 mm/year, and there are different accounts as to whether the rise included a very small deceleration or acceleration. From 1993 to 2012, altimeters have measured a greater sea level trend than the twentieth century trend, but it is not known yet whether this is the leading edge of a sustained acceleration or a fluctuation similar to others that occurred in the twentieth century. The Intergovernmental Panel on Climate Change (IPCC) projected a sea level rise of 0.18 to 0.59 m from 1990 to 2100, but did not include scaled-up ice discharges from ice sheets of Greenland and Antarctica in determining its 0.59 m upper limit. There have been a number of projections of sea level rise to 2100 of 1 to 2 m. These are typically maximum possible projections that do not have probabilities associated with them and, thus, are not directly comparable to the 95%-confidence level projection of the IPCC. Assuming highly improbable/impossible events such as the immediate collapse of the West Antarctic ice sheet with the simultaneous quadrupling of carbon dioxide levels in the atmosphere, sea level could rise as much as 1.7 m by 2100. However, this maximum possible sea level rise by 2100 is not useful in planning and design of flood projects, since it is not typically used even for siting nuclear power plants. Instead, planning and design of flood projects require statistics of sea level projections that are at commensurate probability levels with design-floods. Although IPCC did not fully consider the contributions from Greenland and Antarctica, a recent study that did use IPCC methodology and projects 5, 50, and 95%-confidence-level rises by 2100. Assuming a standard normal distribution, these projections can be used to determine sea level rise probabilities that are consistent with design-flood probabilities. Sea level rise by 2100 will have significant effects on permanent coastal inundation, flooding from episodic events, shoreline erosion and salinity intrusion. The most appropriate response to sea level rise is limiting the long-term rise to a manageable level and

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adaptation to the inevitable rise which will occur. The world must work to reach new agreements limiting carbon emissions and thus limit the long-term rise. But since sea level rise has considerable inertia and will produce an inevitable rise, steps must be taken to adapt to the rise.

## 10.1 Introduction

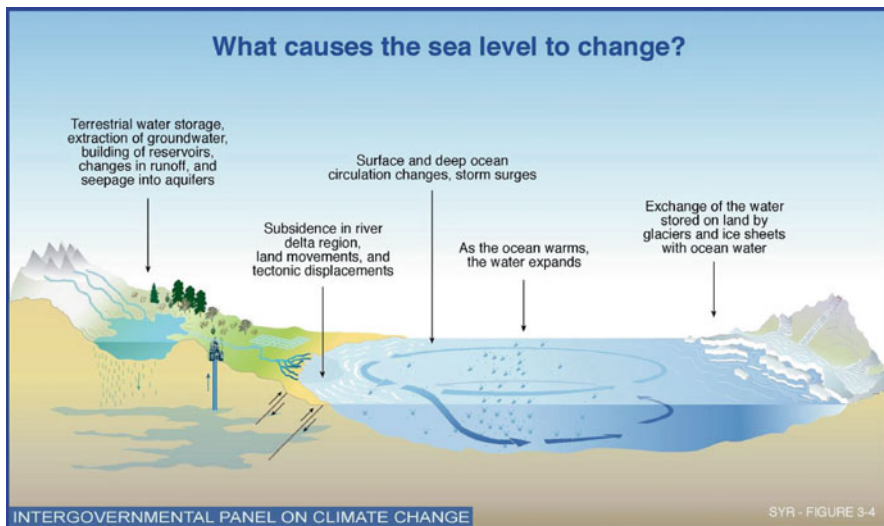
### 10.1.1 *Historical Context*

Sea level has varied over tens of millions of years. During the Paleocene-Eocene Thermal Maximum over 50 Ma, sea level was approximately 75 m higher than today, and the earth was iceless in high latitude areas with alligators living well within the Arctic Circle (Jardine 2011). The remains of deep-ocean-dwelling foraminifera provide a global oxygen-isotope record, which indicates a long-term cooling and sea level fall the past 5 Ma (Lisiecki and Raymo 2005). About 3 Ma ago, the earth began gradually deepening cycles of glacials and interglacials that involved growth and retreat of continental ice sheets in the Northern Hemisphere. Initially cycles lasted about 40,000 years, but a 100,000-year cycle became dominant about a million years ago. These cycles are generally considered to be due to predictable changes in the earth's orbit known as Milankovitch cycles. However, there are a number of unanswered questions about Milankovitch cycles including reasons for the change in the dominant cycle from 40,000 to 100,000 years.

During the Eemian, the last interglacial period about 120,000 years ago, sea level is believed to have been about 4 to 6 m higher than today with temperatures about 2 to 4°C warmer (Jansen et al. 2007). There has been speculation that the Eemian is a good analogue for the response of sea level to future global warming and, therefore, sea level will rise very rapidly in the twenty-first century. However, van de Berg et al. (2011) determined that Northern Hemisphere solar insolation was much greater during the Eemian than today, concluding, "This is why the Eemian melt-temperature relation provides a poor analogue of a future warmer climate. . ." Moreover, Kopp et al. (2009) determined when sea level in the Eemian was close to the current level, the maximum rate of sea level rise was 0.56 to 0.92 m per century. The Intergovernmental Panel for Climate Change (IPCC) projected a 95%-confidence sea level rise for 2100 that falls within this range (Bindoff et al. 2007).

Sea level was about 120 m lower than today during the height of the last ice age about 20,000 years ago (Gornitz 2007). The earth began warming and sea level rising as the earth entered the present interglacial period soon after the peak of the last ice age. The rise of sea level was not constant, but over a period of about 15,000 years, it averaged about 0.8 m a century.

About 5,000 to 6,000 years ago glacial melting had essentially ended, but the earth's lithosphere continued changing in a process known as Glacial Isostatic Adjustment (GIA). GIA is the global response of the earth to changes in ice load



**Fig. 10.1** Contributors to relative sea level change (Interagency Panel on Climate Change)

following the last ice age. Fluid mantle material that was forced away from glaciated areas by the weight of massive ice sheets during the last ice age has been returning to formerly loaded areas, and as a result, there have been horizontal and vertical motions over the entire Earth and changes of the sea surface (Peltier 2001). Global sea level was relatively stable, but slowly increasing during this period.

### 10.1.2 Contributors to Sea Level Rise

Figure 10.1 shows contributors to the sea level rise of about 1.7 mm/year in the twentieth century (Bindoff et al. 2007). Thermal expansion was the primary contributor. Water expands when heated, and in response to global warming, the ocean has been expanding and causing sea level to rise. Melting of glaciers and ice caps also was a major contributor to sea level rise in the twentieth century. There are over 100,000 glaciers and ice caps around the world, many in mountain areas, which are melting and contributing to sea level rise (National Snow and Ice Data Center 2009). The Greenland and Antarctica ice sheets made only small contributions to global sea level rise in the twentieth century, but are expected to make larger contributions in the twenty-first century. Other anthropogenic activities affecting sea level include reservoir impoundment (causing sea level fall) and groundwater extraction (causing sea level to rise, since extracted groundwater eventually finds its way to the ocean through the hydrological cycle). These anthropogenic activities are believed to be almost balanced presently, but

groundwater extraction is expected to make a small contribution to sea level rise in the twenty-first century (Church and White 2011).

Local relative sea level change is caused both by global sea level change and local ground motion and is estimated by subtracting local ground motion (subsidence having a negative sign) from global sea level rise. Local ground motion can be produced by tectonic activity, GIA, subsidence from consolidation of soft sediments, groundwater extraction, and other effects. For example, the ground is rebounding from GIA in high latitude areas of Europe and North America that were weighted down by glaciers during the last ice age, causing a fall in local relative sea level. River delta regions around the world are sinking due to ground subsidence, causing local relative sea level to rise faster than the global average. Relative sea level also is rising faster than the global average at locations such as Chesapeake Bay, United States (US) that bordered ice sheets and were pushed up during the last ice age, but are now subsiding.

## 10.2 Sea Level in the Twentieth Century

Bindoff et al. (2007) estimated a global average sea-level rise of  $1.7 \pm 0.5$  mm/year during the twentieth century. They cited several sources including estimates by Douglas (2001) and Peltier (2001) of 1.8 mm/year over 70 years and Church and White (2006) of  $1.7 \pm 0.3$  mm/year for the twentieth century. Church and White (2011) determined a trend of  $1.7 \pm 0.2$  mm/year from 1900 to 2009 and Ray and Douglas (2011) a trend of  $1.70 \pm 0.26$  mm/year from 1900 to 2007. Thus a twentieth century sea-level rise of about  $1.7 \pm 0.5$  mm/year has become widely accepted.

Several studies have estimated sea-level acceleration. Jevrejeva et al. (2010) analyzed long-term tide gauge recordings at three locations in Europe and concluded that sea level accelerated an average of approximately  $0.01$  mm/year<sup>2</sup> over the past 200 years. Douglas (1992) analyzed global tide gauge records and determined a sea-level change of  $-0.011 \pm 0.012$  mm/year<sup>2</sup> from 1905 to 1985 and  $0.001 \pm 0.008$  mm/year<sup>2</sup> from 1850 to 1991. Church and White (2011) used 17 years of satellite altimeter data to estimate empirical orthogonal functions (EOFs), and in conjunction with historical tide gauge data, estimated accelerations of  $0.009 \pm 0.003$  mm/year<sup>2</sup> from 1880 to 2009 and  $0.009 \pm 0.004$  mm/year<sup>2</sup> from 1900 to 2009. Houston and Dean (2011a) analyzed US tide gauges with record lengths of greater than 60 years, extended the global tide-gauge analysis of Douglas (1992) by 25 years, and analyzed revised data of Church and White (2006) from 1930 to 2007. They obtained small sea-level decelerations varying from about  $-0.001$  to  $0.013$  mm/year<sup>2</sup>. Watson (2011) found sea-level decelerations of  $-0.01$  to  $-0.10$  mm/year<sup>2</sup> in four long Australian and New Zealand tide-gauge records.

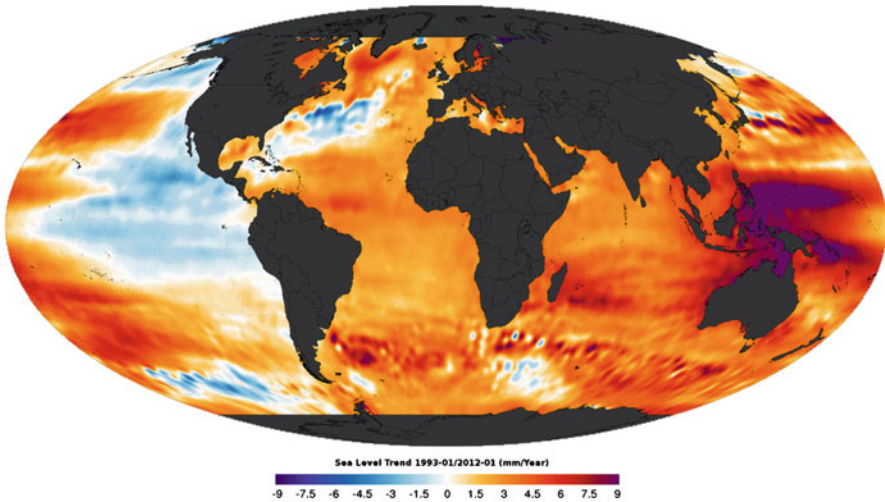
Sea-level acceleration in the twentieth century has generally been estimated to be between about  $-0.01$  and  $0.01$  mm/year<sup>2</sup>, which would produce sea level changes of only  $-0.05$  to  $0.05$  m in 100 years. The rise during the twentieth century

was essentially linear, with either a small acceleration or deceleration producing a relatively small change in sea level. Ray and Douglas (2011) note “near-linearity” in their analysis of data from 1900 to 2007, saying, “. . .there is no statistically significant acceleration in global mean sea level over this period.” They confirm the conclusion of the seminal paper on acceleration by Douglas (1992) that, “There is no evidence for an apparent acceleration in the past 100+ years that is significant either statistically, or in comparison to values associated with global warming.”

### 10.3 Current Sea Level Rise

Three altimeter satellites, TOPEX (Topography Experiment)/Poseidon, Jason-1, and Jason-2, have measured sea level rise since 1993. TOPEX/Poseidon measured from 1993 to past 2002, Jason-1 from about 2002 to 2009, and Jason-2 since 2008. These satellite altimeters have measured sea-level rise of 3.1 mm/year from 1993 to 2012 (University of Colorado 2012), exceeding the twentieth century trend of about 1.7 mm/year. However, the accuracy these measurements has been questioned. Nerem et al. (2010) noted significant bias of unknown origin between the altimeters, determining a bias of about 100 mm between TOPEX/Poseidon and Jason-1 and about 75 mm between Jason-1 and Jason-2. Watson et al. (2004) used GPS buoys and tide gauges and determined that Jason-1 had an absolute bias of 150 mm. These biases are two to three times the total rise of sea level since 1993. Moreover, Domingues et al. (2008) noted that altimeter and tide gauge measurements agree closely up to 1999 and then began to diverge with altimeters recording a greater trend. They say, “It is unclear why the in situ and satellite estimates diverge, and careful comparison is urgently needed.” Disagreement between tide gauge and altimeter measurements is important since tide gauges are used to quantify altimeter bias and drift errors (Nerem et al. 2010).

A few studies have favorably compared tide-gauge and altimeter measurements, but they have shortcomings. Altimeters have recorded remarkable spatial variation in trends over the oceans (Fig. 10.2). Tide gauges are not uniformly distributed across the oceans and therefore miss some of this spatial variation. Therefore, a global trend determined from tide gauges will be biased by an amount dependant on the number of gauges and the degree to which they cover the spatial variation in trend over the oceans. For example, Holgate and Woodworth (2004) compared altimeter measurements with 177 tide gauge records in 13 regions over a 10-year period. However, their tide-gauge records had a significant spatial bias because 7 of the 13 regions were located just in the North Atlantic Ocean (less than 15% of the earth’s ocean area). Prandi et al. (2009) compared altimeter measurements with 91 tide-gauge recordings over a 15-year period. However, they weighted the tide gauge recordings equally, producing a spatial bias, since, for example, they had only a single tide gauge recording in the South Atlantic but nine gauge recordings concentrated around the small Sea of Japan. Church and White (2011) addressed spatial bias by using EOFs to reconstruct tide gauge data, but they noted their



**Fig. 10.2** Altimeter measurements of sea level change 1993–2012 (National Oceanic and Atmospheric Administration)

reconstructed data were determined from altimeter measurements and thus not independent of the measurements.

Dean and Houston (2012) determined trends and accelerations recorded by global tide gauges (456 gauges) during the period of altimeter measurements from 1993 to 2011. They reduced spatial bias by having a large number of gauge records with global distribution. They similarly analyzed altimeter data on a  $1^\circ$  by  $1^\circ$  grid covering the oceans. They determined that the tide gauges measured an average trend of  $3.0 \pm 0.3$  mm/year versus a trend of  $3.1 \pm 0.4$  mm/year measured by the altimeters. Moreover, they developed a method to further reduce the spatial bias due to the tide gauges not being equally distributed and obtained a gauge trend of  $3.0 \pm 0.3$  mm/year. During the 19 years, both the tide gauges and altimeters measured similar decelerations of about  $-0.04$  and  $-0.08$  mm/year<sup>2</sup>. Therefore, global trends and accelerations from tide gauge and altimeter measurements agree over the period of altimeter measurements.

The trend of 3.1 mm/year measured by the altimeters though 2011 is higher than the average twentieth-century trend, but not uniquely high. Jevrejeva et al. (2006) analyzed 1,023 gauge records over the twentieth century and showed the global sea-level trend reached a maximum from 1920 to 1945 that was similar to that measured by the satellite altimeters from 1993 to 2011. Holgate (2007) calculated consecutive, overlapping 10-year mean sea-level trends since 1910 for worldwide gauges and found the altimeters have measured only the fourth highest of six peaks in trend since approximately 1910, with the highest trends of 5.31 mm/year centered on 1980 and 4.68 mm/year centered on 1939. Church and White (2011) used 16-year averages from 1880 to 2010 and found the trend measured by the altimeters was not statistically higher than similar peaks during the 1940s and

1970s. Ray and Douglas (2011) used 15-year averages from 1900 to 2007 and found the trend around 1940 was about the same as that measured by altimeters.

Ablain et al. (2009) showed that 3- and 5-year moving averages of the trend measured by the altimeters have continually declined. The 3-year average recently dropped as low as 1 mm/year and the 5-year average approached 2 mm/year. This deceleration may indicate the increased trend measured by altimeters is a fluctuation similar to others in the twentieth century. However, it cannot yet be determined whether the greater trend measured by the altimeters is the leading edge of a sustained rise or a fluctuation similar to others that have occurred in the twentieth century.

## 10.4 The Threat – Projected Future Sea Level Rise

### 10.4.1 Introduction

Relative rather than global sea level rise is most important at a location. The present relative sea level change can be determined from tide gauge records at locations around the world and is available online from the Permanent Service for Mean Sea Level (PSMSL) data base at <http://www.psmsl.org/data/obtaining/>. The data base is described by Woodworth and Player (2003). GPS data of ground motion at locations near tide gauges can be obtained from Étude d'un Système d'Observation du Niveau des Eaux Littorales (SONEL) at [http://www.sonel.org/IMG/txt/ULR4\\_Vertical-Velocities\\_Table.txt](http://www.sonel.org/IMG/txt/ULR4_Vertical-Velocities_Table.txt). GIA data are available for each tide gauge location in the PSMSL data base at [http://www.psmsl.org/train\\_and\\_info/geo\\_signals/gia/peltier/](http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/).

Adding a complication to sea level projections, global sea level rise will not be the same at all locations. Mitrovica et al. (2010) note that ice melting will produce a variable global sea level rise. Presently, the large ice sheets of Greenland and Antarctica produce a gravitational pull that raises local sea level. As the ice sheets melt, the gravitational force they exert lessens, causing local sea level to fall and the water released to flow to the rest of the globe. Similarly, as ice melts, the ground under the ice sheet begins rising pulling mantle material from other locations, causing the ground to subside at these other locations. The earth's rotation introduces a feedback that also affects the spatial distribution of sea level rise. For example, Mitrovica et al. (2001) show that melting ice in Antarctica will raise sea level in the Northern Hemisphere by about 10 to 20% more than the global average. Similarly, melting of Greenland ice will result in average rises lower than the global average in the eastern US and Europe. Melting of mountain glaciers and ice caps will produce lower rises than the global average in Alaska and the west coast of the US, but higher rises in Australia and the South Pacific. Changes in ocean currents also may change the spatial distribution of sea level rise. Hu et al. (2009) show that melting of the Greenland ice sheet could affect the Atlantic overturning current circulation and subsequently raise sea level on the east coast of the US by 0.1 to 0.5 m by 2100. Finally, Katsman et al. (2008) show that even the

effect of thermal expansion will vary regionally from the global average because changes in water temperature and salinity will not be the same everywhere.

Katsman et al. (2011) demonstrate the spatial variability in sea level rise by estimating the effects on the coast of the Netherlands of regional variations of temperature and salinity, melting of glaciers and ice caps, and melting of the Greenland and Antarctic ice sheets. Because the Netherlands is near the Greenland ice sheet and there are glaciers and ice caps melting in Europe, the net effect of these regional differences was to reduce the projected upper limit of a rise by 2100 on the Netherlands' coast by 0.1 m and the lower limit by 0.15 m. At other locations, these same effects could increase sea level rise above the global average.

#### ***10.4.2 Projected Maximum Possible Sea Level Rise by 2100***

The sea-level-rise section of the 4th IPCC Assessment Report (Bindoff et al. 2007) considered the contribution of ice-sheet melting (called Surface Mass Balance – SMB) in Greenland and Antarctica in its projection of a 95%-confidence level of 0.59 m from 1990 to 2100, but it assumed the flow of ice into the ocean (dynamical ice discharge through marine-terminating glaciers) would continue at rates measured from 1993 to 2003. It estimated sea level could rise an additional –0.01 to 0.17 m above its upper-level projection if the dynamical ice discharge increased linearly with global temperatures. The IPCC typically makes projections from about 1990 to 2100 for comparison purposes, since the first IPCC projections were in 1990.

Projections of sea level rise made by others since the 4th IPCC Assessment Report have typically been higher, generally 1 to 2 m. The difference is usually attributed to greater contributions to sea level rise from the Greenland and Antarctic ice sheets that were projected in these more recent studies. However, a more important factor is that these higher projections are, in general, maximum possible projections with no associated probability, whereas the maximum IPCC projection is at the 95%-confidence level with a 2.5% probability of exceedance. Bindoff et al. (2007) acknowledge that their projection at the 95%-confidence level does not represent the maximum rise that can occur. Projections at the 95%-confidence level and maximum possible projections are not comparable. For most planning and design requirements, projections at the 95%-confidence level or below are appropriate, whereas maximum possible rise projections are rarely appropriate (for example, in the US even siting of nuclear power plants is done at the 99.95%-confidence level and not the maximum possible level).

Nicholls et al. (2011) survey a number of projections of sea level rise by 2100 and from them select what they call a “pragmatic” range of 0.5 to 2.0 m. The 0.5 m is based on a 0.48 m projection by the IPCC at the 95%-confidence level for a mid-level temperature rise scenario of 4.4° C by 2100. However, a level of 0.48 m at the 95% confidence level means that there is only a 2.5% chance that the sea level rise



by 2100 will be greater than 0.48 m, so this is an upper and not lower limit for this scenario.

The upper level of 2.0 m selected by Nicholls et al. (2011) was said to be unlikely to occur and of “unquantifiable probability” and was based on studies projecting rises up to 2.4 m. The upper limit of 2.4 m is from a projection by Rohling et al. (2008) of  $1.6 \pm 0.8$  m that is based on analogy with the rise during the Eemian. Although not covered by Nicholls et al. (2011), Hansen (2007) and later Hansen and Soto (2011) similarly cited the Eemian period and projected sea level rise of 5 m by 2100. However, as mentioned in the Introduction, recent studies show that the Eemian is a poor analogue of sea level response to projected warming by 2100, and the maximum sea level rise in the Eemian when sea level was similar to today was only 0.56 to 0.92 m per century.

Pfeffer et al. (2008) considered glaciological conditions necessary to support projections of multi-meter sea level rise by 2100. They noted the contribution to sea level rise of the Greenland and Antarctic ice sheets consists of SMB and dynamical ice discharge of glaciers into the ocean. They estimated SMB contributes about 30% of the present rise in sea level due to the ice sheets but would only constitute about 4% to a rise of 2 m by 2100. Thus dynamical ice discharge was the major mechanism that could produce large rises in sea level. Their key assumption was that increased temperatures would increase glacier sliding velocities into the ocean. Pfeffer et al. (2008) showed that achieving a rise of 2 m by 2100 would require glacier sliding to accelerate over a decade to velocities an order of magnitude greater than current velocities, and even greater velocities would be required if there were a delay in onset. They noted such velocities far exceed the fastest motion exhibited by any outlet glacier and concluded that increases in sea level greater than 2 m by 2100 were “physically untenable”.

The key assumption made by Pfeffer et al. (2008) was that increased temperatures will increase velocities of glacier sliding. This assumption is based on the concept that meltwater during summer months percolates through the glacier and lubricates the ice/rock interface, thereby causing the glaciers to slide more rapidly. A recent study by Sundal et al. (2011) at six Greenland glaciers, however, shows that although this effect causes glaciers to begin sliding during summer months, the warmer the summer, the slower the sliding velocity. They found that during warmer summers the velocity of ice flow was only about 60% of the flow during cooler summers. During warmer summers, there is greater meltwater, but the water begins running off in channels with apparently less water percolating down to the ice/rock interface. With less water lubricating the interface, movement of ice slows during warmer summers compared to cooler summers. Sundal et al. (2011) noted that the same phenomenon was observed by Bingham et al. (2003) and Truffer et al. (2005) for mountain glaciers. Van de Wal et al. (2008) measured a 17-year decrease in the velocity of flow of a Greenland glacier during a period of increased melting due to global warming. Moreover, IPCC (2010) noted that glaciers in southeast Greenland slowed during the recent period of increased temperatures. These observations of actual glacier response to warming invalidate

the key assumption of Pfeffer et al. (2008) and are indicative of the cap in sea level rise by 2100 being less than 2 m.

Nicholls et al. (2011) also considered Rahmstorf (2007) and Vermeer and Rahmstorf (2009) in determining the upper level projection of 2.0 m. Rahmstorf (2007) was the first study that used a “semi-empirical” modeling approach to forecast sea level rise of 0.5 to 1.4 m from 1990 to 2100. His approach attempted to link sea level rise with temperature rise. A subsequent paper by Vermeer and Rahmstorf (2009) increased the rise to 0.75 to 1.9 m. These papers have been criticized in the peer reviewed literature by Holgate et al. (2007), Schmith et al. (2007), Taboada and Anadon (2010), and Houston and Dean (2011b). Since contributions to sea level rise from thermal expansion and glaciers and ice caps are fairly well understood, these relatively large projections hinge on large contributions from the Greenland and Antarctic ice sheets. However, as noted by IPCC (2010), the semi-empirical models were calibrated during past periods of time when contributions from Greenland and Antarctica were almost insignificant. Conditions in the future that are expected to lead eventually to large contributions from Greenland and Antarctica were not acting during the calibration period, leading to questions about how the models could then project into the future.

Rahmstorf (2007) and Vermeer and Rahmstorf (2009) were followed by a series of studies by three authors using semi-empirical models. These studies have received little criticism in the peer-reviewed literature. Jevrejeva et al. (2010), Grinsted et al. (2010), and Jevrejeva et al. (2011) projected rises by 2100 of 0.6 to 1.6, 0.9 to 1.3, and 0.57 to 1.10 m respectively. However, in a recent IPCC workshop (IPCC 2010) attended by over 100 participants who are experts on sea level rise and the Greenland and Antarctic ice sheets, the participants considered semi-empirical models and concluded, “No physically-based information is contained in such models . . .” and “The physical basis for the large estimates from these semi-empirical models is therefore currently lacking.”

With a portion of the Netherlands below present sea level, the Dutch have a significant interest in projections of sea level rise by 2100 and cannot afford to under predict the rise. Katsman et al. (2011) consider a “severe scenario” of temperature rise that includes the beginning of the collapse of the West Antarctic ice sheet, and they project a global rise by 2100 of up to 1.15 m. Although they consider a “severe” scenario, their maximum projected rise is not the maximum possible rise.

The maximum possible rise can be estimated by determining a cap based on a series of improbable/impossible events. For example, the greatest contribution of Antarctica to sea level rise by 2100 would be a collapse of the West Antarctic ice sheet. The East Antarctic ice sheet is expected to contribute a slight reduction in sea level by 2100, so the worst-case scenario would be collapse of the West Antarctic ice sheet. Bamber et al. (2009) considered sea level rise should the West Antarctic ice sheet collapse and concluded that it could raise sea levels by between 1.9 and 6.4 mm/year. If the collapse were to occur immediately, it would raise sea level from 2012 to 2100 by between 0.17 and 0.56 m. Similarly, Katsman et al. (2011)

consider the rise of sea level should the West Antarctic ice sheet collapse, and they estimate a rise of 0.41 m. So, 0.56 m is likely the maximum possible rise.

Huybrechts et al. (2011) used a global ocean–atmosphere model and determined that sea level would rise only about 0.18 m after quadrupling of carbon dioxide in the atmosphere. Similarly, Ridley et al. (2005) used an ocean–atmosphere model to estimate the contribution that Greenland would make to sea level given a quadrupling of carbon dioxide in the atmosphere. They simulated 3,000 years, and the most rapid contribution to sea level rise during the period was 5 mm/year. The maximum possible rise would be for a contribution from Greenland of 5 mm/year that would begin immediately and produce a rise by 2100 of 0.44 m.

The expected contribution of thermal expansion and glaciers and ice caps outside Greenland and Antarctica to sea level is reasonably well known. Taking the “severe” scenario considered by Katsman et al. (2011), thermal expansion could add 0.49 m and glaciers and ice caps 0.20 m to sea level rise from 1990 to 2100.

Adding all contributions (including the rise of sea level from 1990 to 2012 from Greenland and Antarctica), the maximum possible global rise from 1990 to 2100 would be about 1.7 m. This is a cap on the rise, since it is a sum of highly unlikely/impossible events. This maximum possible rise by 2100 would decline every year that the West Antarctic ice sheet did not collapse and Greenland did not contribute 5 mm/year to a global rise. For example, if neither event occurs in the next 10 years, the projection to 2100 decreases to about 1.6 m. The most recent projections of contributions from Greenland and Antarctica do not point toward rises that would be close to this cap. For example, Graversen et al. (2010) projected a contribution by 2100 from Greenland of 0.0 to 0.17 m and the Arctic Monitoring Assessment Programme (2011) a contribution of 0.10 to 0.19 m. Huybrechts et al. (2011) used an earth-systems numerical model and determined a high-scenario rise for Greenland of about 0.18 m per century over a 500-year period. Greve et al. (2011) used two different global models and projected a total contribution of 0.12 to 0.22 m. Similarly, barring collapse of the West Antarctic ice sheet, Katsman et al. (2011) projected a contribution to sea level rise by 2100 from Antarctica of only –0.01 to 0.07 m.

### ***10.4.3 Projections for Planning and Design Using IPCC Methodology***

Maximum possible projections are not useful for project planning and design. For example, in the US, many flood projects are typically designed at the “100-year” flood level (1% chance of being equaled or exceeded in any given year) and even nuclear power siting is designed at the 100,000-year flood level (99.998%-confidence level) and not the maximum possible level.

IPCC methodology provides a range of sea level rise projections with associated probabilities that can be chosen to be consistent with the design-flood probability.

For example, the 100-year flood has a 63% probability of occurring within a 100-year period. The 95%-confidence level projection of IPCC has only a 2.5% chance of exceedance in 100 years and, therefore, is not at a consistent probability level with the 100-year design-flood probability.

Bindoff et al. (2007) did not fully consider contributions of Greenland and Antarctica to sea level rise by 2100, but will undoubtedly do so in its next report due in 2013 to 2014. However, Houston (2012) provides sea level rise projections for 2100 using IPCC methodology and considering the latest trend and acceleration ice-mass losses in Greenland and Antarctica based on satellite measurements. He then adds contributions from thermal expansion and melting of glaciers and ice caps based on information published since Bindoff et al. (2007), obtaining sea level rise projections from 1990 to 2100 of 0.18, 0.48, and 0.82 m at 5, 50, and 95%-confidence levels respectively. Since his projections of individual contributions to sea level rise from Greenland, Antarctica, thermal expansion, and melting of glaciers and ice caps compare favorably with projections in several recent studies, it is likely that the 5th IPCC assessment report will project similar levels from 1990 to 2100

The IPCC methodology can be used to match design-flood levels and sea level rise projections at consistent levels of accuracy by assuming a standard normal distribution. For example, the Dutch plan for the 10,000-year coastal flood level. A 98%-confidence level for sea level rise by 2100 has the same 1% chance of exceedance as the 10,000-year flood has of occurring within 100 years. Using Houston (2012) and assuming a normal distribution, the 98%-confidence sea level rise by 2100 is 1.1 m. Katsman et al. (2011) in a study of sea level rise on the coast of the Netherlands obtained a similar global sea level rise by 2100 of 1.15 m for a “severe scenario” that included collapse of the West Antarctic ice sheet. In the same way, IPCC methodology can be used to match design flood levels and sea level rise with other design-flood levels.

## **10.5 Coastal Hazards from Future Sea Level Rise**

### ***10.5.1 Introduction***

Gornitz (1991) notes there are four basic coastal hazards from relative sea level rise – permanent inundation, episodic inundation, increased erosion, and saltwater intrusion of estuaries and aquifers. The vulnerability of coastlines to these threats depends strongly on relative sea level rise. This in turn depends on the average global sea level rise, local variations of sea level rise from the average global rise, and local ground motion. For example, formerly glaciated areas as in parts of Canada or Fennoscandia that are now rebounding with the ground moving up rapidly have a low vulnerability, whereas river delta areas such as the Nile delta

of Egypt, where the ground is sinking rapidly, are highly vulnerable. Impacts depend on factors such as the degree of coastal development and options a local population may have. Sea level rise might not cause great impacts on a coast with little development, whereas an entire low-lying island might be threatened by sea level rise, with the population having no long-term option other than abandonment.

### ***10.5.2 Permanent Inundation***

Sea level rise will cause permanent inundation in low-lying areas. Areas most at risk are river deltas, chenier plains, estuaries, lagoons, mudflats, bays, and low-lying islands. River deltas such as those of the Nile, Indus, Irrawaddy, and Ganges-Brahmaputra are heavily populated. In addition to global sea level rise, river deltas are subsiding due to sediment consolidation along with lesser amounts of sediment reaching river deltas due to a variety of causes. Milliman et al. (1989) estimated that within the next 100 years, over 25% of the land of Bangladesh and over 20% of habitable land in the Nile delta could be lost. Populations on low-lying islands cannot retreat from sea level rise by moving inland – the entire island is at about the same height. Coral islands increase in elevation due to coral growth, but Gornitz (1991) notes that maximum calcification growth is about 10 to 12 mm/year, so if sea level rises faster than 1 to 1.2 m/century, coral islands will eventually be inundated.

It is difficult to estimate the impact on populations and economic activity of permanent land inundation from sea level rise by 2100, because there is not a good accounting of the population and economic activity that will be affected. Global data are not available any finer than the 10-m land contour. So, for example, McGranahan et al. (2007) report that 2% of the world's land area and 10% of its population are within 10 m of sea level. Nicholls et al. (2011) estimate that a 0.5 to 2.0 m sea level rise will inundate approximately 0.6 to 1.2% of the world's land area. They note that this could displace 53 to 125 million people in east, southeast, and south Asia alone.

Coastal wetlands will be greatly affected by sea level rise. Salt marshes respond to rising sea level by vertical accretion based on sedimentation. However, with sea level rising, local subsidence, and often reduced levels of sedimentation, coastal wetland loss will increase. Gornitz (1991) estimated that a 1.4 m rise in sea level would lead to 40% of US coastal wetlands lost.

### ***10.5.3 Episodic Inundation***

Episodic inundation will have a greater impact on populations and economic activity than simple inundation. In many parts of the world, tropical and extra-tropical storms, backwater flooding of rivers, and tsunamis can affect people up to the 10-m elevation and beyond. Thus the estimate by McGranahan et al. (2007) that

10% of the world's population lives within 10 m of sea level has significance. Meehl et al. (2007) noted that models suggest an increase in intensity of both tropical and extra-tropical storms. Nicholls et al. (2007a) show in a study of the world's 130 largest port cities that flooding due to storm surge exposes 40 million people to the 1-in-100-year coastal flood event. They estimate that this number will increase to 150 million by the 2070s due to the combined effects of sea level rise, increased storminess due to climate change, coastal subsidence, population growth, and increased urbanization. They estimate assets exposed to this threat were 5% of total global Gross Domestic Product in 2005 (about US\$3 trillion) and 9% by the 2070s (about US\$35 trillion). Miami, US, was projected to have the highest property and infrastructure exposure by the 2070s, with more than US\$3.5 trillion of exposed assets, followed by Guangzhou, China, with US\$3.3 trillion exposure and New York, US, with US\$2.1 trillion.

Although 1-in-100-year flooding events may seem relatively rare, Nicholls et al. (2007a) note that the annual probability of one of the 130 port cities having a 1-in-100 year event is almost 75% and the probability over 5 years is almost 100%. Higher sea levels provide a higher base for storm surges, extending the range of flooding. For example, the US Federal Emergency Management Agency (1991) estimated that rises in sea level of about 0.3 and 0.9 m by 2100 would increase the area flooded in the US by the 100-year flood event from about 31,000 km<sup>2</sup> to 37,000 and 43,000 km<sup>2</sup> respectively. Because of this expanded flood zone and expected growth in the coastal population, the number of flood-prone households was estimated to increase from approximately 2.7 million to 5.7 and 6.8 million by the year 2100 for the 0.3 and 0.9 m scenarios, respectively. It estimated an increase in the expected annual flood damage by the year 2100 for a representative insured property to increase by 36 to 58% for a 0.3 m rise and by 102 to 200% for a 0.9 m rise.

#### ***10.5.4 Increased Erosion***

Nicholls et al. (2007b) note that many coasts are eroding, but it is unclear as to the extent erosion is due to relative sea level rise versus human activities (e.g., sediment loss from dredging, interruption of littoral drift by coastal structures and navigation channels, sediment supply loss from upland dams). However, the "Bruun rule" (Bruun 1962) is often used to project shoreline erosion from sea level rise. The Bruun rule states that for a shoreline profile in equilibrium, as sea level rises, shore erosion takes place in order to provide sediments to the nearshore so the nearshore bottom can be elevated in direct proportion to the rise in sea level. The Bruun rule became increasingly cited after Dubois (1976) showed it explained shoreline response at a location in Lake Michigan in the United States as lake levels varied. However, relatively rapid changes in lake level may not a good model for the relatively slow rise in sea

level, and the adequacy of the Bruun rule to project shoreline change due to sea level rise has been challenged (Cooper and Pilkey 2004).

A recent study by Absalonsen and Dean (2011) analyzed a remarkable data set that covers almost 140 years of shoreline change over 1,162 km of shoreline along the east and west coasts of Florida, US. Even accounting for sand nourishment of Florida beaches in the modern era, it appears that this coastline has been stable for 140 years despite rising sea level. With relative sea level in Florida increasing at approximately 2 mm/year, the Bruun rule would predict average shoreline loss of about 15 to 30 m during the 140 years. The Bruun rule only considers offshore movement of sediment, but these Florida data are indicative of onshore movement of sediment that compensates for sea level rise. Dean (1991) discusses how onshore sediment transport can modify shoreline response to sea level rise. In addition, the production of calcium carbonate (e.g., shells) by organisms may play a part, since Pilkey et al. (2006) show that the fraction of calcium carbonate in beaches from North Carolina to Florida in the US increases rapidly to the south with one beach in Florida having about 40% of its beach sand consisting of calcium carbonate. The Florida data are indicative of onshore movement of sediment in response to sea level rise and may invalidate simple estimates of shoreline response to sea level using the Bruun rule. In addition, it is possible that there will be regional differences in shoreline response based on the activity of calcium-carbonate-producing organisms.

### ***10.5.5 Salt Water Intrusion***

Rising sea level will allow saltwater to penetrate farther inland and upstream, affecting both surface and groundwater supplies. Saltwater intrusion will affect water supplies for urban and agricultural use and harm aquatic plants and animals. The Ghyben-Herzberg principle (Poehls and Smith 2009) says that the distance of the freshwater lens below sea level in a coastal aquifer is 40 times the freshwater's height above local mean sea level. Thus, each increment in sea level rise reduces the thickness of the freshwater lens by a factor of 40.

South Florida, US, is a good example of the challenges that saltwater intrusion caused by sea level rise will pose to ecosystems and human water supplies. Saha et al. (2011) note that the 0.3 m sea level rise measured at Key West, Florida, over the past century (along with human diversions of surface water) has resulted in saltwater intrusion in the Everglades up to 30 km inland. The intrusion is changing the ecosystem from freshwater-dependent species to halophytes, threatening 21 rare coastal species. At the same time, water supplies to urban areas and agriculture in South Florida is threatened. Wiedenman (2010) notes that 90% of the population in highly urban south Florida use groundwater. The saltwater/freshwater interface has been creeping landward and is as far inland as 8 miles in parts of Miami. He lays out alternatives that Miami is considering to address the problem including moving wells inland, treating brackish water from the Florida Aquifer, and desalinating ocean water. The plight of south Florida is not unique. For example, Kashef (1983)

reports that that salt-water intrusion in the Nile Delta extended inland 130 km from the Mediterranean.

### ***10.5.6 Adaptation***

Nicholls et al. (2007b) note that sea level rise has a substantial inertia, and the most appropriate response to sea level rise is a combination of adaptation to the inevitable rise and mitigation to limit the long-term rise to a manageable level. They note that adaptation costs for vulnerable coasts are much less than the costs of inaction. However, they also note that adaptation will be more challenging for developing countries than developed countries because of shortfalls in financial resources and capabilities.

Nicholls et al. (2007b) outline coastal adaptation strategies that should be part of an integrated coastal zone management approach. Various retreat alternatives could be part of this approach, including moving of populations and structures out of vulnerable areas, “set back lines” for new construction, and other zoning approaches to reduce vulnerabilities. Retreat options would have to be supported by public education about the threats and adequate information from flood-hazard mapping. There could be an accommodation to sea level rise by flood-proofing or elevating buildings. Coastal assets could be protected by either advancing the coast line by reclaiming land, as has been done for some airports, or closure of estuaries as done by the Dutch in defense of the Netherlands. The present coastline position could be maintained through building dikes or nourishing beaches with sand.

Nicholls and Tol (2006) demonstrate the significant benefits that can be obtained by adaptation. In one case, they consider flood protection against storm surge through dike construction and beach nourishment. They show that with no adaptation, as many as 100 million additional people will experience annual flooding due to sea level rise by the 2080s. If various defense schemes are built, the number drops to about 5 to 15 million people. Nicholls et al. (2011) show there are substantial costs in providing this protection. They estimate annual costs, including maintenance costs, to provide dike and beach nourishment protection at \$25 to \$270 billion (1995 values) for 0.5 and 2.0 m sea level rises by 2100. They estimate in 2100 the relative mix of nourishment, dike construction, and dike maintenance at 36, 39, and 25% for a 0.5 m rise and 13, 51, and 37% for a 2.0 m rise.

A world-wide adaptation response will be very uneven. Nicholls et al. (2007b) highly recommend an integrated coastal zone management approach. The US is a good example of the difficulties in establishing a coordinated and integrated response to the sea level threat. Each of the 50 states in the US has its own coastal management plan. The federal government is not responsible for construction setback lines or local zoning decisions. It can influence coastal construction through its federally-backed flood insurance program, but the



maximum insurance it provides against flooding is generally much lower than the cost of building on the coast, so coastal construction in the US has not slowed. Building of coastal dikes and beach nourishment in the US are generally shared costs at the national, state, and local level. However, states and local governments and even the private sector can make their own decisions with the only requirement being the need to obtain permits that are generally environmentally related.

In addition to the adaption response likely being uneven in individual countries, Nicholls et al. (2007b) point out the problems with developing countries not having the financial capabilities to adapt to the challenges of sea level rise. There are programs that provide aid to developing countries to address these challenges, but the aid is presently inadequate and is expected to be even more inadequate as problems become more acute. The world community has the opportunity to champion integrated coastal zone management plans when funding adaptation in developing countries. However, it is expected that adaptation will be financed primarily in developed countries and driven by cost versus benefit and available resources. There are tools being developed such as the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel and Klein 2009) that can aid in developing alternatives in an integrated coastal zone management approach.

## 10.6 Summary and Conclusions

Sea level rise in the twentieth century was 1.7 mm/year, and there are different accounts as to whether the rise included a very small deceleration or acceleration. From 1993 to 2012, altimeters have measured a greater sea level trend than the twentieth century trend, but it is not known yet whether this is the leading edge of a sustained acceleration or a fluctuation similar to others that occurred in the twentieth century. The IPCC (Bindoff et al. 2007) projected a sea level rise of 0.18 to 0.59 m (95%-confidence level) from 1990 to 2100, but did not include scaled-up ice discharges from ice sheets of Greenland and Antarctica in determining its 0.59 m upper limit. There have been a number of projections of sea level rise to 2100 of 1 to 2 m. These are typically maximum possible projections that do not have probabilities associated with them and, thus, are not directly comparable to the 95%-confidence level projection of the IPCC. Assuming highly improbable/impossible events such as the immediate collapse of the West Antarctic ice sheet with the simultaneous quadrupling of carbon dioxide levels in the atmosphere, sea level could rise as much as 1.7 m by 2100. However, this maximum possible sea level rise by 2100 is not useful in planning and design of flood projects, since it is not typically used even for siting nuclear power plants. Instead, planning and design of flood projects require statistics of sea level projections that are at commensurate probability levels with design-floods. Although Bindoff et al. (2007) did not fully consider the contributions from Greenland and Antarctica, a recent study that did

uses IPCC methodology and projects 5, 50, and 95%-confidence-level rises by 2100. Assuming a standard normal distribution, these projections can be used to determine sea level rise probabilities that are consistent with design-flood probabilities. Sea level rise by 2100 will have significant effects on permanent coastal inundation, flooding from episodic events, shoreline erosion and salinity intrusion. The most appropriate response to sea level rise is limiting the long-term rise to a manageable level and adaptation to the inevitable rise which will occur. The world must work to reach new agreements limiting carbon emissions and thus limit the long-term rise. But since sea level rise has considerable inertia and will produce an inevitable rise, steps must be taken to adapt to the rise. These steps should be guided by integrated coastal zone management approaches in each country. However, even with the best of intentions, adaptive responses will likely not be uniform and will be pursued mainly in developed countries where the cost of protection is outweighed by benefits.

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