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Roger Revelle Lecture 2006

Global Sea Levels
Past, Present and Future

by John Church

Reprint from IOC Annual Report 2006

UNESCO 2007

Celebrating...one of the founders of the IOC of UNESCO:

The Roger Revelle Medal

Roger Revelle (1909-1991) was a pioneer in oceanography and in global ocean science cooperation. He was one of the first scientists to cite a potential for human-induced climate change. His 1979 address on climate to the Eleventh IOC Assembly was a typical Revelle *tour de force*. As one of the first scientists to point to the role of the ocean in the climate system and in climate variability, he began '*I am about to describe what I believe to be the most important programme that has challenged the IOC in many years.*'*

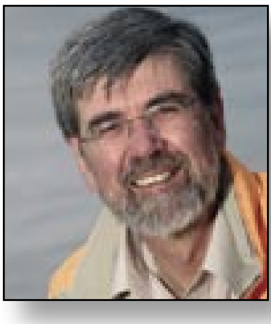
Roger Revelle was convinced that the efforts required for an adequate study of the ocean exceeded the capabilities of any one country, and accordingly, he was one of the founders of the Intergovernmental Oceanographic Commission of UNESCO.

In 1991 the IOC established a memorial lecture named after Roger Revelle. Every two years the IOC Roger Revelle Memorial Lecture addresses climate related oceanographic science, and institutional co-operation in this field and in general, at the national and international levels.

To formally honour Revelle's focal role in helping to create the IOC, Dr Patricio Bernal, IOC's Executive Secretary, announced the award of a 'Roger Revelle Medal' to all Revelle Memorial Lecturers, starting on the occasion of the Thirty-seventh Executive Council, 2004. The Roger Revelle Medal recognizes outstanding contributions to the ocean sciences by inspired researchers who communicate their knowledge and global vision of the challenges facing our Planet in order to shape a better future for humankind.

* Extract courtesy of 'Roger Revelle and his contribution to International Ocean Science' by the honourable John A. Knauss, Revelle Memorial Lecture, 1992

Global Sea Levels: Past, Present and Future



John Church is an oceanographer with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research and the Antarctic Climate and Ecosystems Cooperative Research Centre. He has published across a broad range of topics in oceanography; his area of expertise is the role of the ocean in climate, particularly anthropogenic climate change. He is co-editor of the book *Ocean Circulation and Climate* (2001)[1]. He was co-chair of the international Scientific Steering Group for the World Ocean Circulation Experiment from 1994 to 1998 and is now chair of the Joint Scientific Committee of the World Climate Research Programme (WCRP). He has been a Principal Investigator on NASA/CNES Topex/Poseidon and Jason-1 Science Working Teams since 1987. He was co-convening lead author for the chapter on sea level in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. He co-chaired the recent WCRP Understanding Sea level Rise and Variability Workshop, hosted by the IOC in Paris, France.

John Church was awarded the 2006 Roger Revelle Medal by the Intergovernmental Oceanographic Commission of UNESCO in 2006 and was the recipient of a CSIRO Medal for Research Achievement in 2006. The 2006 Roger Revelle Lecture he presented at the IOC's Thirty-ninth Executive Council and the report from the sea level workshop form the basis of this report.

1. *Ocean Circulation and Climate*, G. Siedler, J. Church, and J. Gould, (eds), Academic Press, 2001.

The oceans are a central part of the global climate system. As Roger Revelle, one of the founders of the Intergovernmental Oceanographic Commission of UNESCO, said many years ago, 'The oceans exert a profound influence on mankind and indeed upon all forms of life on Earth. The oceans are inexhaustible sources of water and heat, and control the climate of many parts of the world.' Revelle also recognized that 'human beings are now carrying out a large-scale geophysical experiment of a kind that could have not have happened in the past nor be reproduced in the future'. These ideas have even more importance today as we continue to alter the Earth's atmosphere with far reaching consequences for climate, conditions in the ocean and at the coast, and the habitability of our planet. What will be the impact of this experiment? What are the consequences?

One of the major consequences of climate change is rising sea levels, the focus of a World Climate Research Programme Workshop hosted by the IOC in 2006, and opened by the Executive Secretary of IOC, Patricio Bernal. The WCRP and IOC, with the generous support of the conference co-sponsors, were able to bring together many of the world's leading scientists, representatives of developing nations, and students to the workshop in Paris.

Does rising sea level matter?

We love the ocean and the coasts. Millions of people are crowded along the coastal fringes of continents, attracted by recreational opportunities, coastal and deep-sea fishing and rich fertile land. In excess of 150 million people live within 1 metre of high tide level; 250 million within 5 metres of high tide [1]. Many of the world's megacities, cities with populations of many millions, are situated at the coast, in addition to coastal infrastructures worth billions of dollars.

The impacts of sea level rise include inundation of low-lying coastal regions, particularly during extreme sea level events, coastal erosion of beaches, saltwater intrusion into coastal aquifers, deltas and estuaries, damage to coastal ecosystems, water resources and coastal infrastructure. Coastal regions at most risk include heavily populated deltaic regions, small islands, especially atolls, and sandy beaches backed by major coastal developments, and of course a number of the world's megacities located on the coast.

Has sea level changed in the past?

Sea level has varied by over 100 metres during glacial-interglacial cycles as the

The statement from the WCRP Understanding Sea Level Rise and Variability Workshop, hosted by the IOC in Paris, is available at http://wcrp.wmo.int/AP_SeaLevel.html. A full meeting report will be published by Blackwell Publishing.

Fig. 1. Billions of dollars of coastal infrastructure has been built immediately adjacent to the coast. *(Photo of the Gold Coast, Australia by Bruce Miller.)*

major ice sheets have waxed and waned. Sea level was about 4 to 6 metres above present day values during the last interglacial period, when Greenland was about 3 °C warmer than today. Meltwater from the Greenland ice sheet was probably the largest single contributor to this higher sea level [2]. During the last ice age, sea level fell to more than 120 metres below present day levels as water was stored in the North American, the Northern European and the Antarctic ice sheets. As the ice melted, starting around 20,000 years ago, sea level rose rapidly at average rates of about 10 mm/yr (1 metre/century), and with peak rates of the order of 40 mm/yr (4 metres/century), until about 6,000 years ago [3].

The last few thousand years

Over the last 6,000 years, sea level rose much more slowly, with a decreasing contribution in the last few thousand years. Sea level data inferred from the location of ancient Roman fish tanks dated about 2,000 years before present indicate that there has been little net change in sea level from that time until the start of the nineteenth century [4]. Changes in local sea level estimated from sediment cores collected in salt marshes [5,6,7] have revealed an increase in the rate of sea level rise in the western and eastern Atlantic Ocean during the nineteenth century or early twentieth century, consistent with the few long tide gauge records from Europe and North America.

The rate of sea level rise over the last 20 years is 25 per cent faster than any rate during the previous 115 years, almost twice as fast as the average over the twentieth century, which was in turn an order of magnitude larger than the rate of rise over the two millennia prior to the eighteenth century.

The historical record

Coastal and island tide gauge data show that sea level has risen by just under 20 cm between 1870 and 2001, at an average rate of 1.7 mm per year during the twentieth century and an increase in the rate of rise over this period [8], consistent with the geological data and the few long records of sea level from coastal tide gauges (Figure 2). From 1993 to the end of 2006, near global measurements of sea level (between 65 °N and 65 °S) made by high quality satellite altimetres (and estimates from coastal and island tide gauges) indicate global average sea level has been rising at 3.1 ± 0.4 mm per year [9]. The uncertainty estimates of about 0.4 mm/yr relate primarily to satellite calibration and reference frame issues. The rate of sea level rise over the last 20 years is 25 per cent faster than any rate during the previous 115 years, almost twice as fast as the average over the twentieth century, which was in turn an order of magnitude larger than the rate of rise over the two millennia prior to the eighteenth century.

Why is sea level rising?

The two major reasons for sea level rise are thermal expansion of ocean waters as they warm and an increase in the ocean mass, principally from land-based sources of ice

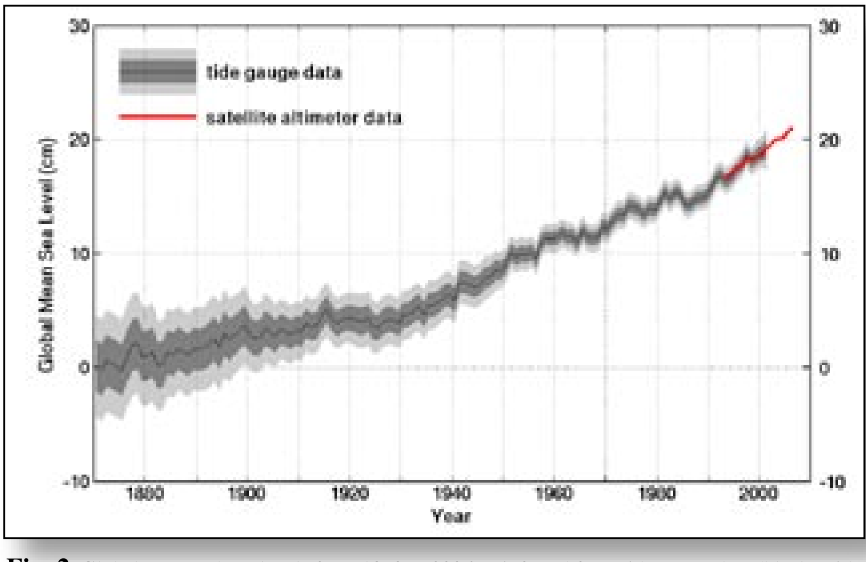


Fig. 2. Global averaged sea levels from 1870 to 2006 as inferred from tide gauge data (black, with 66% and 95% confidence limits given in dark and light shading) and satellite altimeter data (red). (Updated from Church and White, 2006 [8])

(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.

From 1955 to 1995, ocean thermal expansion is estimated to have contributed less than 25 per cent of the observed rise [10]. However, for 1993 to 2003, when the best data are available, thermal expansion is estimated to be significantly larger at about 50 per cent of the observed sea level rise of 3.1 mm per year [11]. The melting of glaciers and ice caps (excluding the glaciers surrounding Greenland and Antarctica) contributed about 25 per cent of the observed rise for both the 1961 to 1990 period and the satellite altimeter period since 1993 [12].

The ice sheets of Antarctica and Greenland [13] have the potential to make the largest contribution to future sea level rise, but they are also the greatest source of uncertainty. Since 1990, there has been increased accumulation at high elevation on the Greenland ice sheet, while at lower elevation there has been more widespread surface melting and a significant increase in the flow of outlet glaciers. The net result is a decrease in the mass of the Greenland ice sheet – a positive contribution to sea level rise. For the Antarctic ice sheet, there is greater uncertainty. Over recent years, increased glacier flow on the Antarctic Peninsula and the West Antarctic ice sheet are thought to dominate increased thickening of the East Antarctic ice sheet. There are insufficient data to make direct estimates over the preceding decades but modelling studies suggest that the Antarctic ice sheet is still responding to changes since the last ice age and thus contributing to sea level rise.

The difference between the sum of the contributions to sea level rise and the observed rise from 1993 to the present is smaller than the estimated errors. However for the 1961 to 2003 period, ocean thermal expansion and the melting of glaciers and ice caps and a reasonable allowance for an ice sheet contribution do not adequately explain the observed rise [14]. One possible reason for this discrepancy is the inadequate ocean database, particularly for the deep and southern hemisphere oceans, leading to an underestimate of ocean thermal expansion. Recent studies are revealing [15], and beginning to develop ways to deal with, long-term instrumental biases. Early results in our own studies are suggesting that allowing for these issues as well as the inadequate historical ocean database may lead to some reduction in these discrepancies. Of course there is also an inadequate database for assessing historical changes in the cryosphere. Changes in the terrestrial storage of water (changes in lakes, building of large and small dams, seepage into aquifers and mining of ground water) may also be important but the sum of these contributions in poorly known. Model studies suggest significant interannual variability of the climate related components of terrestrial water storage but with little long-term trend [16].

Projections of future sea level change

During the twenty-first century, sea level will continue to rise due to warming from both past (twentieth century and earlier) and twenty-first century greenhouse gas emissions. Ocean thermal expansion is likely to be the dominant contribution to twenty-first century sea level rise, with the next largest contribution coming from the melting of glaciers and ice caps.

Recent estimates indicate that non-polar glaciers and ice caps may contain only enough water to raise sea level by 15 to 37 cm [13]. As they melt in a warming climate, the glaciers at lower altitude and latitude reduce in size significantly, reducing their contribution to the rate of sea level rise.

For Greenland [13], both glacier calving and surface melting contribute to mass loss. Over the last few decades surface melting has increased and is expected to dominate over increased snowfall leading to a positive contribution to sea level during the twenty-first century. For the majority of Antarctica [13], present surface temperatures, and those projected for the twenty-first century, are too cold for significant melting to occur. Antarctic precipitation is balanced by glacier flow into the ocean. For the twenty-first century, climate models project an increase in snowfall, resulting in increased storage of ice in Antarctica, partially offsetting other contributions to sea level rise. However, this increase in precipitation has not been observed to date.

In addition to these surface processes, there are indications of a potential dynamical response of the Greenland and Antarctic ice sheets. In Greenland, there was a significant increase in the flow rate of many of the outlet glaciers during the early twenty-first century. One potential reason is increasing surface melt making its way to the base of the glaciers, lubricating their flow over the bedrock, consistent with increased glacier flow during the summer melt season [17]. However, a recent study has shown the flow rate of at least two of these glaciers has recently decreased to near their earlier rates, suggesting that there is significant short-term variability in glacier flow rates [18].

Another potential factor is the role of ice shelves in restraining the flow of outlet glaciers. The rapid break up of the Larsen B ice shelf in the Antarctic Peninsula was followed by a significant increase in the flow rate of the glaciers previously feeding this ice shelf, suggesting that the ice shelves played a role in restraining the flow of the outlet glaciers [19]. However, some modelling studies suggest this is a transient acceleration. Another important consideration is that the West Antarctic ice sheet is grounded below current day sea level. As the ice sheet thins and starts to float, warm ocean water can penetrate beneath and enhance melting at the base.

All of these dynamic ice sheet processes, in both Greenland and West Antarctica, could lead to a greater rate of sea level rise than in current projections. However, the processes are inadequately understood and are not included in the current generation of ice sheet models. It is therefore not possible to make robust quantitative estimates of their twenty-first century and longer-term contributions to the rate of sea level rise.

Projections of twenty-first 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 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 [3]. 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) [14], the sea level projections using a much larger range of models are 18 to 59 cm (90 per cent confidence limits) over the period from 1980-2000 to 2090-2100. Allowing for the ice sheet uncertainties discussed above, IPCC AR4 increased the upper limit of the projected sea level rise by 10 to 20 cm and stated 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 TAR and AR4 projections are somewhat different in how they treat ice sheet uncertainties and the confidence limits quoted, a comparison of the projections (Figure 3) shows the end results are somewhat similar, except that the lower limit of the TAR projections has been raised from 9 to 18 cm.

From the start of the IPCC projections in 1990 to 2006, observed sea level has been rising more rapidly than the central range of the IPCC model projections and near the upper end of the total range of the projections [20] shown in Figure 3, indicating that one or more of the model contributions to sea level rise is underestimated. Indeed in recent work, a simple statistical model relating twentieth century surface temperature change to twentieth century sea level change suggests that the projected surface temperature increases may lead to a twenty-first century sea level rise as large as 1.4 metres [21], somewhat larger than the IPCC projections.

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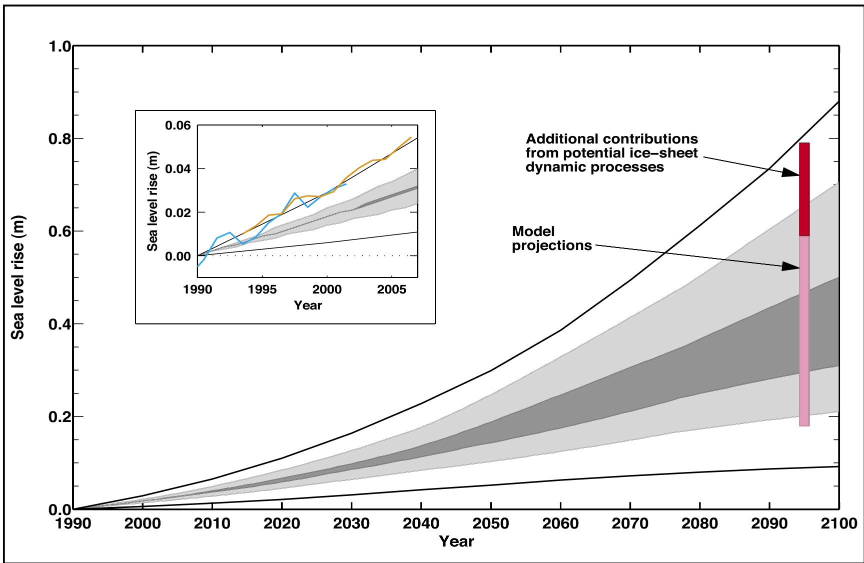

Fig. 3. Projected sea level rise for the twenty-first century. The projected range of global averaged sea level rise from the IPCC 2001 Assessment Report [3] for the period 1990 to 2100 is shown by the shaded regions. The updated AR4 IPCC projections made in 2007 are shown by the bars plotted at 2095: purple bar for the model projections (90% confidence limits) and red bar for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic ice sheets to global warming [14]. 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 observed sea levels from tide gauges (blue) and satellites (orange) tracked along the upper bound of the IPCC 2001 projections since the start of the projections in 1990. Based on Church et al. 2001[3]; information added from IPCC 2007 [14] and Rahmstorf et al. [20]

Longer-term projections

For the next few decades, the rate of sea level rise is partly locked in by past emissions, and will not be strongly dependent on early twenty-first century greenhouse gas emission. However, sea level projections closer to and beyond 2100 are critically dependent on future greenhouse gas emissions, with both ocean thermal expansion and the ice sheets potentially contributing metres over centuries for higher greenhouse gas emissions. There is increasing concern about the longer-term contributions of the ice sheets. For example, for the Greenland ice sheet, a global average temperature increase relative to pre-industrial values of greater than 3.1 °C (with a range of 1.9 °C to 4.6 °C) leads to surface melting exceeding precipitation, resulting in an ongoing wastage of the Greenland ice sheet for centuries and millennia [22], consistent with sea levels in the last interglacial being several metres higher than today's value. This threshold or 'tipping point' could potentially be crossed late in the twenty-first century if effective mitigation measures are not adopted. A second cause for concern is associated with the poorly understood dynamic responses of the Greenland and West Antarctic ice sheets (as discussed above) that could lead to a significantly more rapid rate sea level rise than from surface melting alone.

The regional distribution of sea level rise

Climate variations and change cause the redistribution of ocean volume and sea level. From 1993 to 2006, the rate of sea level rise was not uniform [23]. There were much larger values approaching 20 mm/yr, or ten times the global average, in the western Pacific Ocean and the eastern Indian Ocean, and lower values in the eastern Pacific Ocean and the western Indian Ocean. There are even regions where sea level fell during this period. This pattern of sea level rise is a result of natural variability, including the transition from El Niño-like conditions at the start of the altimeter record to more La Niña-like conditions at the end of the record.

When zonally averaged around the globe, the maximum rates of sea level rise were at mid to high latitudes in both hemispheres. That is at the location of the Kuroshio in the North Pacific and the Antarctic Circumpolar current in the Southern Ocean. In the Southern hemisphere this is associated with changes in the wind patterns and a poleward movement of the major oceanic features. The sea level change associated with changing ocean temperatures is very similar to that for total sea level change, indicating that the pattern of sea level rise is largely associated with changing ocean temperatures. Clearly, changes of sea level in deep ocean regions are critical for understanding coastal impacts.

Fig. 4. One example of the impacts of extreme events has been the devastation left by Hurricane Katrina. *Photo Courtesy of U.S. Army*

At this stage there is no agreed pattern for the longer-term regional distribution of projected sea level rise although there are several common features in model projections (for example, a maximum in sea level rise in the Arctic Ocean and a minimum in the Southern Ocean south of the Antarctic Circumpolar Current [24]).

The large transfers of mass from the continents to the oceans associated with glacial interglacial conditions mean large changes in the surface load of the Earth and as a result vertical movement of the Earth's surface. The Earth is still responding to the changes that have occurred since the last glacial maximum. Far from the former ice sheets, these land motions are small, perhaps a few tenths of a millimetre per year, often with the land rising. Present day changes of surface loading also contribute to large-scale vertical motion of the Earth's surface [25].

Vertical land motion also occurs on a regional and local scale. Withdrawal of groundwater and drainage of susceptible soils can cause significant subsidence. Subsidence of several metres during the twentieth century has been observed for a number of coastal megacities. Reduced sediment input to deltas is an additional factor that causes loss of land elevation relative to sea level.

Extreme events

Climate change, including the impact of sea level rise, will be felt most acutely through extreme events. One example of the impacts of extreme events has been the devastation left by Hurricane Katrina. The Bay of Bengal with its low-lying deltas has been an area of major impact of coastal storm surges. Here there have been 23 surge events that have killed at least 10,000 people (per event) since 1937, with over 300,000 people killed in 1970.

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There have been few global scale studies of changes in extreme events because of the difficulty of assembling a global high-frequency data set. The few studies to date indicate that there has been a trend towards increased frequency of extreme events of a given level over the last several decades for many locations, i.e. these locations are experiencing more frequent coastal flooding events [26]. However, the few studies of sea level extremes have generally not yet indicated an increase in the intensity of extreme events compared to a changing mean sea level.

Any increase in the intensity of tropical cyclones [27,28], as indicated in some analyses of observations and as suggested should occur in theoretical studies, will result in a further increase in the intensity of extreme coastal flooding events. However, this area remains controversial and affected by the changing quality of historical data over time. This is clearly an area of major importance in need of urgent attention.

Improving our ability to adapt to sea level rise

Adaptation to both increases in sea level and any change in extreme events requires local planning based on local scientific information. Providing this local information requires improving our understanding at local, regional and global scales and across a wide range of scientific disciplines. The WCRP sea level rise workshop hosted by the IOC agreed on the priorities for research and observations (see the Workshop Statement available at http://wcrp.wmo.int/AP_SeaLevel.html).

Of prime importance is the development of the Global Climate Observing System, including the Global Ocean Observing System. An open data policy is needed with timely, unrestricted access for all. Efforts in data archaeology to extend records back in time with quality control are also needed. To the extent possible, satellite observations need to be as continuous as possible, with overlap between successive missions and coincident with the collection of appropriate *in situ* observations.

Priorities include sustained, systematic observations of:

- Sea level (extension of the Jason series of satellite altimetres and completion of the Global Sea Level Observing System (GLOSS) network of tide gauges, with absolute positioning and real-time data availability).
- Ocean volume (the Argo array of pro-

Fig. 5. Flood victims collecting survival assistance, Bangladesh, August 2004. *© World Food Programme*

filing floats for the upper ocean and its extension to ice covered regions and the design and implementation of a deep ocean observing system).

- Ocean and terrestrial mass (observations of the time-varying gravity field to contribute to estimating changes in terrestrial water storage, ice sheet mass balance and changes in oceanic mass).
- Ice sheet and glacier topography and thickness and ice velocity.
- Two-dimensional surface water levels on land.

These observations need to be done in the context of a strengthened International Terrestrial Reference Frame. Of course these observation programmes must be backed by ongoing research and improvement in climate and ocean models and analyses.

Key Messages

There is clear scientific consensus that sea level is rising in response to past emissions of greenhouse gases from human activity. At the same time, we are living ever closer to the coast and coastal development is continuing to occur. Many of the world's major megacities are on the coast and growing rapidly. These developments will make the issue of climate change and sea level rise even more acute.

A major concern is: 'will we pass a tipping point during the twenty-first century leading to essentially unstoppable melting of the Greenland ice sheet and a sea level rise of several metres from Greenland melting alone?'

If we only stabilize greenhouse gas emissions, sea level will continue to rise from ocean thermal expansion and melting of the Greenland ice sheet. These trends would result in sea levels rising metres over hundreds of years.

A major concern is: 'will we pass a tipping point during the twenty-first century leading to essentially unstoppable melting of the Greenland ice sheet and a sea level rise of several metres from Greenland melting alone?'

It is important to recognise that the ocean and the ice sheets have long response times. Stabilization of greenhouse gas concentrations (requiring a reduction in emissions) would result in surface temperatures rising at a much slower rate for decades. However, ocean thermal expansion only decreases slowly and thus sea level rise will continue (albeit more slowly) for centuries. Lower greenhouse gas stabilization concentrations would result in less ocean thermal expansion.

These long response times mean that no matter how successful we are in mitigating the emission of greenhouse gases, we will need to adapt. The impacts of sea level rise will be felt most acutely through extreme events – coastal flooding events of a given level will occur more frequently and the largest flooding events will be more severe. Least developed countries and the poor are most at risk. Increasing numbers of environmental refugees will be an inevitable consequence of

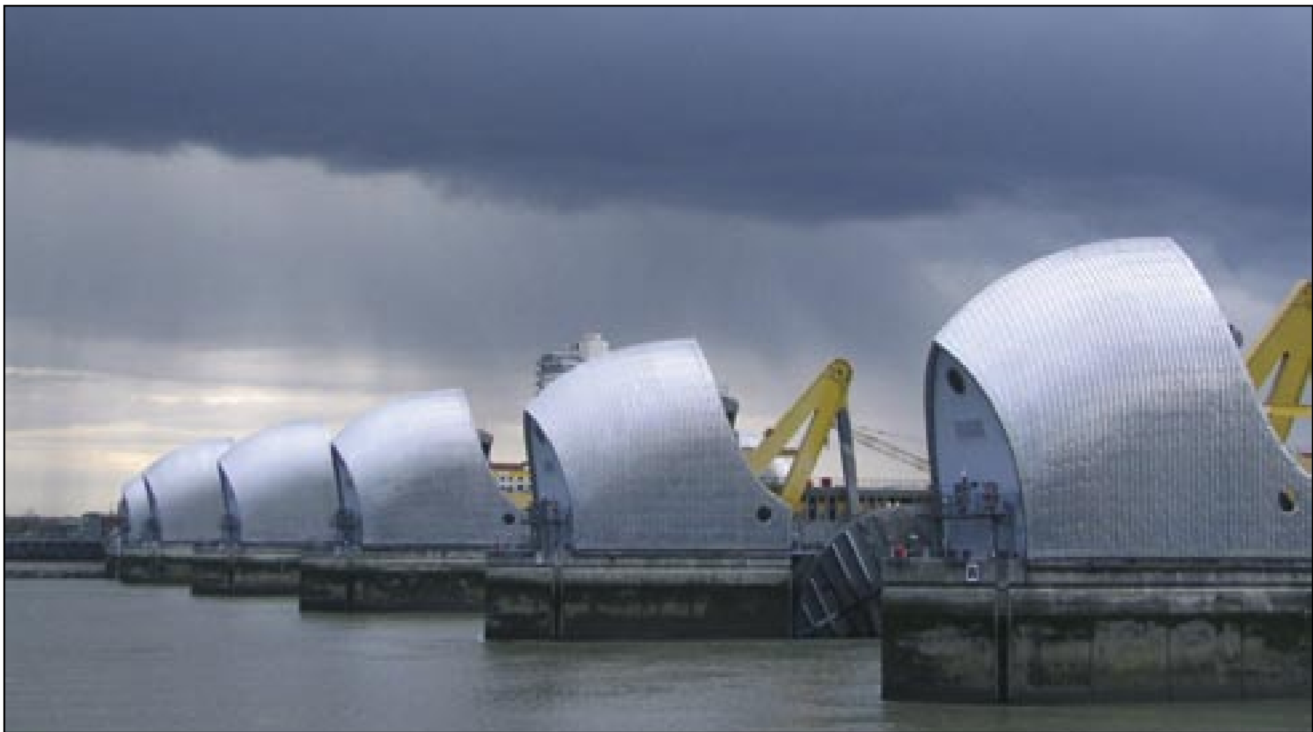

Fig. 6. Plans are being formulated to upgrade the Thames Barrier to protect the City of London from rising sea levels and storm surges. *Photo courtesy of Brian Micklethwait*

continued sea level rise. Environmental refugees are a here and now issue; it is not 'if' but when, where and how will we respond.

Successful adaptation could significantly reduce the impacts of sea level rise. For adequate adaptation planning, we need to narrow the current uncertainties and we need to develop partnerships between science, governments, business and the community. It is important we start planning early. One example of early planning is the investment of billions of pounds to upgrade the Thames Barrier (Figure 6) to protect the City of London from rising sea levels and storm surges.

Sea level rise is happening now and is beginning to have real impacts. It is an issue for the here and now, for the twenty-first century and for the long term.

A personal outlook

I wonder what Roger Revelle would think today? When he made his prophetic statement about a grand experiment with Planet Earth about fifty years ago, he did not know the consequences of the experiment or its impact on humanity. We are slowly learning what the consequences might be. This knowledge is revealing the need to determine more precisely the results of the experiment, for urgent action to mitigate and avoid sea level rise of metres, and to adapt to the impacts of climate change, including sea level rise. The IOC has an important leadership role in these actions. It is critical that the IOC recognises and addresses these challenges.

Acknowledgements

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