GLOBAL WARMING AND SEA-LEVEL RISE

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NEW PERSPECTIVE ON GLOBAL WARMING & SEA LEVEL RISE: MODEST FUTURE RISE WITH REDUCED THREAT

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ABSTRACT
Sea Level Rise (SLR) in response to the present and future warming of the earth's surface is probably the most contentious issue being debated at present. This brief commentary surveys the most recent literature on ongoing SLR and on the major factors contributing to future rise. It is concluded that the best guess value of SLR for the next 100 years is a relatively modest 23 cm +/– 5 cm which poses little threat to coastal areas of the world either at present or in future.

INTRODUCTION

The topic of Sea Level Rise (SLR) on regional and global scale and its possible linkage to the present and future warming of the earth's surface is perhaps the most intensely debated issue on climate change at present. A recent Google search shows an astounding 1.8 M listings on global warming & sea level rise issue. Many articles in national & international news papers, popular scientific magazines as well as in scientific journals discuss the possibility of SLR as high as 3 to 7 m as a result of melting of Greenland and Antarctic Ice Sheets due to warming of the earth's surface by 3C or more in the next 100 years. In a recent comprehensive paper (Wunsch et al 2007), the lead author Prof (emeritus) Carl Wunsch states: '*modern sea level rise is a matter of urgent concern from a variety of points of view, but especially because of the possibility of its acceleration and consequent threats to many low-lying parts of the inhabited world*'. Recent satellite altimetric data by the TOPEX/Poseidon satellite (Leuliette 2004) suggest that since about 1993, global SLR has been rising at a rate of 2.8 +/– 0.4 mm per year and this has raised the possibility of "accelerated SLR due to significant melting of high-latitude Ice Sheets"

The IPCC (Intergovernmental Panel on Climate Change) in its 1995 climate change documents estimated SLR of about 50 cm by 2100. In the 2001 climate change documents the IPCC revised this estimate to about 37 cm. In the most recent IPCC assessment, Meehl (2007) projects SLR to be between 14 and 43 cm (with a mean value of 29 cm) by 2100 under the A1B (greenhouse gas) emission scenario in which the earth's mean temperature is projected to rise between 2.3C and 4.1C

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by 2100. In view of the large disparities between these estimates and between the estimates of the ongoing rate of rise and the projections for the future, it is the purpose of this article to take a closer look at some of the recent studies to determine the best possible value of SLR for the next 50 to 100 years.

A BRIEF HISTORICAL PERSPECTIVE

It is now generally accepted that the global sea level increased by about 120 m as a result of deglaciation that followed the last glacial maximum (LGM) about 21,000 years ago. By about 5000–6000 BP (Before Present), the melting of high-latitude ice mass was essentially completed (Douglas & Peltier 2002). Thereafter global sea level rise was small and appears to have ceased by 3000–4000 yr BP. Rates of global-averaged SLR over the last 1000 yr and prior to the twentieth century are estimated to be less than 0.2 mm/yr (Fleming et al 1998; Lambeck 2002). The late 20th century SLR is most intriguing and has sparked several studies in the last fifteen years. A study by Holgate & Woodworth (2004) using 177 tide gauges divided into 13 regions with near global coverage obtains a value of 1.7 +/– 0.2 mm/yr over a 55-year period (1948–2002). Another study (Church et al 2004) estimates regional distribution of SLR for the period 1950–2000 by combining satellite altimeter data with historic tide gauge data. The study obtains a value of 1.8 +/– 0.3 mm/yr for the 51-year period (1950–2000) with a maximum value of over 2 mm/yr over the North Atlantic Ocean along a band running east-northeast from the US east coast. Among major sources of uncertainty identified by Church et al are inadequate distribution of tide gauges particularly in the southern hemisphere, inadequate information on various geophysical signatures in the tide gauge data (e.g. glacial isostatic adjustment and tectonic activity) and relatively short duration of satellite altimetric data. In a series of comprehensive studies Peltier and coworkers (Peltier 1996, 1998, 2001; Douglas & Peltier 2002) have articulated the issue of GIA (Glacial Isostatic Adjustment) which refers to the gradual springing back of the earth's crust in response to the removal of the ice loads of the LGM which were at their maximum extents around 21000 yr BP. Peltier and his students (University of Toronto Canada) have developed a geophysical computer model which accounts for gravitational interaction between a spherical viscoelastic model of the solid earth and the surface mass load associated with the process of glaciation and deglaciation. This numerical model documents how the GIA is a slow process that decays exponentially at a rate determined by the (earth's) mantle viscosity. The GIA is still significant in the region around the Gulf of Bothnia (often referred to as Fennoscandia) which was covered with ice to a depth of several kilometers during the LGM and where the relative sea level is currently falling at a rate of 5–10 mm/yr as the land in that region continues to rebound. In another comprehensive study Munk (2002) examines the *twentieth century sea-level rise enigma* and assesses various geophysical forcing (like earth's rotation, polar wandering etc) as well as climate forcing (melting of glaciers, thermal expansion of water, El Nino events) on the SLR for the 20th century. Munk concludes that *despite large error bars in SLR estimates, the traditional value of 1.5–2 mm/yr seems a reasonable estimate for the 20th century SLR*.

RECENT STUDIES

Since the publication of IPCC (2007) climate change documents, several studies have appeared on sea level rise and related issues. A few of the important recent studies are summarized below:

1. **Holgate (2007):** This study examines nine long and almost continuous sea-level records to obtain SLR estimates for the period 1904–2003. The rate of SLR was found to be larger in the first half of the 20th century (2.03 +/− 0.34 mm/yr 1904–1953) than in the second half of the century (1.45 +/− 0.34 mm/yr 1954–2003). According to Holgate, the highest decadal rate of rise occurred in the decade centered on 1980 (5.31 mm/yr) while the lowest rate of rise occurred in the decade centered on 1964 (−1.49 mm/yr).
2. **Wunsch et al (2007):** This comprehensive study obtains regional estimates of sea level trends using over 100 million data points generated by a 23-layer general circulation model with a 1° horizontal resolution. The general circulation model uses many different types of data including salinity, sea surface temperature, satellite altimetry and Argo float profiles over a period 1993–2004. The study finds large regional variability, governed by thermal, salinity and mass redistribution contribution. Based on a careful analysis of such a large data base, the authors obtain a global mean value of SLR as 1.6 mm/yr which is about 60% of the pure altimetric estimate of 2.8 mm/yr, as mentioned earlier. The authors also identify several uncertainties and regional variations in the altimetric data and conclude that *"it remains possible that the database is insufficient to compute sea level trends with the accuracy necessary to discuss the impact of global warming—as disappointing as this conclusion may be"*
3. **Jevrejeva et al (2008):** In this study the authors examine the global sea level acceleration in the context of recent satellite data (TOPEX/Poseidon) and conclude that present sea level acceleration (~0.01mm/yr^2) began over 200 years ago. The authors suggest that if this sea level acceleration continues, then a value of 34 cm for the total SLR by the end the 21st century would be expected. The authors further suggest faster sea level rise than IPCC estimates due to thermal inertia of oceans and higher melt rates from Greenland Ice Sheets.
4. **Wopplemann et al (2008):** This study examines one of the world's longest tide gauge records, at Brest (France), and concludes that the Brest tide gauge is stable over the period 1889–2007. These authors further conclude that the sea level rise at Brest has been at a constant rate for over 100 years and as such the rise does not appear to be influenced by rapid increase in atmospheric CO_2 of the last fifty years.

DISCUSSION

Based on various numbers provided in the studies mentioned above, a value for SLR in the range of 1.6–1.8 mm/yr is obtained for the recent fifteen years or so. This value tacitly incorporates the climate-change components, namely the steric rise due to thermal expansion and the eustatic rise due to ice sheet melting. To project future SLR, it is necessary to closely analyze how the earth's climate may warm in future and how this warming may impact future melting of ice sheets and glaciers. Examination of several recent papers leads to the following discussion:

a. Future steric rise: Three recent papers discuss the issue of climate sensitivity (mean temperature increase for a doubling of carbon dioxide concentration) and obtain future temperature increase as just about 1C to 1.5C (Chylek & Lohmann

2008; Lindzen 2007; Schwartz 2007). Chylek & Lohmann consider aerosol radiative forcing and climate sensitivity from LGM to Holocene transition and obtain a range of 1.2C to 2.3C for climate sensitivity. Lindzen analyzes recent mid-tropospheric temperature changes and obtains a value of just 1C for climate sensitivity, while Schwartz analyzes ocean heat capacity and storage and obtains a value of 1.1C for climate sensitivity. These and other related studies (e.g.,Lindzen & Giannistis 2002) suggest the best guess value for climate sensitivity to be about 1.2C (with a 95% confidence range of 0.9C to 2.0C).

The mean temperature of upper ocean and the global SST (Sea Surface temperature) distribution is another important parameter in determining the steric component of future SLR. Several recent studies (Lyman et al 2005; Gureteski & Koltermann 2007; Willis et al 2009; Lohle 2009) now suggest no significant warming of the upper ocean in the last few years. The recent study by Lohle (2009) obtains a cooling of upper ocean from 2003 to 2006 by about 0.35×10^{22} J, thus suggesting a decline in ocean heat storage at present. Also the SST profile over global ocean shows a steady decline for the past few years as shown in Figure 1. This Figure shows a peak value of SSTs around 1997/98, this peak value being associated with the intense El Nino of 1997 (see Arun Kumar et al 2001). Since about 2005, the SSTs are on a declining path as shown.

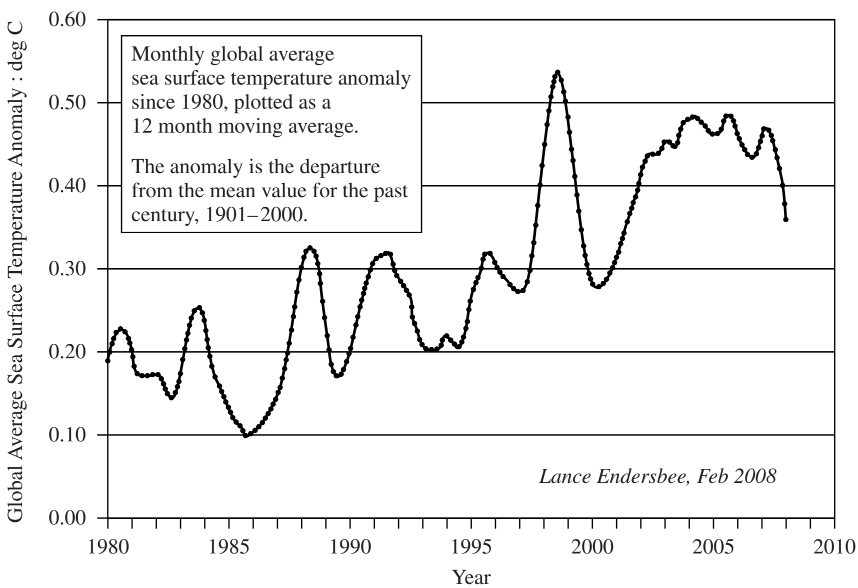

Figure 1. Global average sea surface temperature anomalies plotted as a 12-month moving average. (Source: (late) Prof Lance Endersbee, Australia)

According to IPCC projections (Meehl 2007), the thermal expansion will be the largest component of SLR contributing to 230 +/− 100 mm by 2100. Taking into account the declining SSTs and a low value of climate sensitivity as discussed above, the thermal (or the steric) component of future SLR can be estimated to be just about 45% of IPCC projections OR about 100 mm (with a 95% confidence range of 75 to 125 mm). The 95% confidence range is arrived at using Holgate's (2007) estimate.

b. Future eustatic rise: The issue of melting of mountain glaciers as well as melting of the Greenland Ice Cap and the Antarctic Ice Sheets is once again being debated in news media and also in scientific literature. There have been a number of recent news items about melting of Greenland as well as Antarctic Ice Sheets. These news items together with publication of more recent studies have sparked renewed concern about escalating SLR due to melting of world-wide glaciers and ice sheets. Among several papers published in the last few years, two papers are of interest here. A paper by Raper & Braithwaite (2006) makes a careful assessment of melting of mountain glaciers (outside of Greenland Ice cap & Antarctic Ice Sheets) and obtains a revised estimate of about 50 mm (5 cm) over next 100 years. The most recent paper on glacier melting and SLR is by Bahr et al (2009) and obtains a lower bound of 184 mm (18.4 cm) for SLR due to melting of world's glaciers and mountain caps, even if the climate does not continue to warm along current trends. Bahr et al use satellite remote sensing technology to obtain AAR (Accumulated Area Ratio) values for a number of glaciers. These AAR values, together with mass balance data for about 86 glaciers allow Bahr et al to obtain a value of 184 mm as the minimum (eustatic) contribution to future SLR. This value (184 mm) appears to be high in light of the reality of climate change over the 20th century as will be demonstrated by the following analyses. It is now well-established that the Arctic Basin temperature rose sharply in the 1920s and 1930s and the Arctic was at its warmest in 1935/36 during the first half of the twentieth century. A paper by Chylek et al (2005) compares the warming of the Arctic between 1920–1930 and 1995–2005 and demonstrates that the Arctic warmed at a faster rate in the 1920s than in the 1990s and in the first few years of the new millennium. In a related paper Vinther et al (2006) extend Greenland temperature records to 1874 using long-term temperature records from the Danish Meteorological Institute. The paper further documents that the decades 1930s and 1940s were the warmest decades in Greenland and 1941 was the warmest year in the 135-year temperature record of Greenland. In view of these observational studies, it is surmised here that the Arctic glaciers as well as the Greenland Ice Cap may have experienced rapid melting from 1920s through 1940s, but no estimate of any melt rates or of AAR were available due to lack of satellite remote sensing technology in the 1920s and 1930s. The observed world-wide SLR from about 1940 till 2008 is now known to be about 12 cm of which only about 6 to 8 cm rise can be attributed to the possible melting of Greenland Ice Cap together with other Arctic mountain ice caps (see Munk 2002). As for the melting of the Antarctic Ice Sheets, a paper by Zwally et al (2005) provides some guidance. This paper makes a comprehensive assessment of changes in ice mass in Greenland and also in the Antarctic for the period 1992–2002 and obtains a maximum SLR as just about 0.1 mm/yr. In view of more recent studies and news items on 'rapid melting' of the Antarctic, an upper bound of 0.5 mm/yr OR a value of 50 mm for the next 100 years can be used as the possible maximum contribution to future SLR due to melting of the Antarctic. When all the above numbers are added, we get a total contribution to the SLR over next 100 years as:

1. *steric component: 10 cm +/– 2.5 cm*
2. *eustatic component: 8 cm (Arctic)+ 5 cm (Antarctic) = 13cm +/– 2.5 cm*
   Total SLR for next 100 years: 23 cm +/– 5 cm

CONCLUDING REMARKS

The best guess value for SLR for the next 100 years appears to be about 230 mm (23 cm) with a 95% confidence interval of +/–50 mm. In view of cooling of the upper oceans observed in recent years and a possible continued cooling of the earth's mean temperature over the next decade (e.g., Keenlyside et al 2008), the best guess value of SLR from now until 2025 is estimated to be just about 30 mm with a 95% confidence interval of +/–10 mm. This estimate is significantly lower than the range projected by the IPCC fourth assessment report in 2007. In terms of climate policy, such a value of future sea level rise poses no major threat to the coastal regions or low-lying countries (e.g., Bangladesh, The Maldives, Tuwalu) of the world at present or in the foreseeable future.

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