Informing Adaptation to Sea Level Rise: The Need for a Decadal Local Sea Level Forecasting Service

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Abstract - The extremely stable Global Sea Level (GSL) experienced by human civilizations during the last ~7,000 years has led many to believe that sea level in general changes slowly on global down to local scales. However, as recent as during the last deglaciation, rapid Local Sea Level (LSL) changes altered coast lines within decades. But large-scale built environment was absent, and the much smaller number of human beings living in coastal zones could easily adopt to shifting coast lines. Today, with wide-spread built environment and crucial, potentially polluting infra-structure in coastal zones, rapid changes in coast lines and increased inundation risks during storm surges would be economically and environmentally devastating. In the absence of actionable century-scale GSL and LSL predictions, and in the face of low-probability but extremely high-impact rapid LSL events, there is a growing societal need for actionable forecasts of LSL changes on decadal time scales. To a certain extent, a decadal sea level forecasting service would be comparable to the ongoing sky-watch for near-Earth objects: detecting the low-probability, high-impact event in a timely manner to reduce the impact. Since contributions of the ice sheets to GSL changes are particularly uncertain, key elements of a decadal LSL forecasting service would be a Global Cryosphere Watch (GCW) and models capable of assimilating GCW and other observations as a basis for reliable decadel LSL forecasts. Such a service could facilitate mitigation and adaptation where and when necessary. Setting up such a service now would enable the assessment of its predictive capabilities.

1. INTRODUCTION

Global warming is likely to lead to a significant rise in Global Sea Level (GSL) with potentially devastating impacts on coastal cities and settlements (e.g., Rowley et al., 2007), including a "*displacement through flooding and tropical storm activity of up to 332 million people in coastal and low-lying areas*" (Watkins et al., 2007). The societal and economic impacts would be felt globally. Loss estimates for single major disasters due to storm surges and hurricanes hitting urban coastal areas in the U.S. are in excess of $100 billion for the immediate damages (e.g., Chapman et al., 2006, Jacob, 2007). Even the slow increases in GSL projected by IPCC AR4 (Meehl et al., 2007) would change the risks associated with storm surges and hurricanes, potentially leading to extreme disasters in coastal areas with dense urban settlements. A rapid LSL rise over a few decades would amplify the risks and the ensuing disasters. Considering the high costs of adaptation and of potential disasters caused by coastal hazard, both over and under-protection/adaptation can be very costly and significantly impact national economies. Adaptation may require relocation of settlements (e.g., Vellinga, 2007) and major infrastructure, including railroads, highways, and airports (e.g., CCSP, 2008).

Over the last fifteen years, an increasing number of risk assessments have been carried out nationally (e.g., CCSP, 2008), and internationally (e.g., Hulme et al., 2002, Anthoff et al., 2006, Plag et al., 2006a, Tol et al., 2006, Rowley et al., 2007, Katsman et al., 2011). Following the IPCC AR4, most of the recent assessments do not assume a significant contribution from the ice sheets. Recent research has shown that dynamic links between climate and cryosphere are becoming more active (e.g., surface melt influence on ice sheet flow, Zwally et al., 2002, and ice dynamic response to ocean/ice interaction, Motyka et al., 2003, Holland et al., 2008). Moreover, the unexpected observed recent changes in the large ice sheets (e.g., Rignot et al., 2008a, 2008b), including the acceleration of the mass loss in the Greenland and Antarctic ice sheets reported by Velicogna (2009), as well as accelerated melting of glaciers and ice caps (Meier et al., 2007, Pfeffer et al., 2008, Kierulf et al., 2009) indicate that an early onset of significant non-linear responses of the cryosphere cannot be excluded, thus opening for a significant GSL rise already over the next two to three decades. Current ice models cannot provide reliable long-term predictions of such a dynamic response (Lipscomb et al., 2009), and a major uncertainty for GSL predictions is associated with the contribution from glaciers and ice sheets. In summary, the recent assessments demonstrate that currently future LSL variations are not predictable on century time scales. The wide plausible range of Local Sea level (LSL) trajectories and large uncertainties in the associated Probability Density Functions (PDF) greatly reduce the value of these long-term assessments for risk management. Even with respect to the upper end of the range of plausible future LSL trajectories, large uncertainties exist, and recent scientific papers have sent an unclear and mixed message to the decision makers and the public (see, e.g., the comments in the New York Times in 2008 and 2009 on recent papers such as Pfeffer et al., 2008, Vandewal et al., 2008, Rignot et al., 2008a, Blanchon et al., 2009, Hu et al., 2009, Mcphee et al., 2009). Thus, predictions of GSL rise and coastal Local Sea Level (LSL) for the 21st century do not provide actionable information.

Increasingly, the possibility of a rapid LSL rise not captured by any of the recent assessments is recognized. During the last deglaciation, rapid LSL altered coast lines within decades. However, during that time, large-scale built environment was absent, and with much lower populations, human beings could easily adopt to shifting coast lines. Today, with substantial built environment and crucial infrastructure in coastal zones, rapid changes in coast lines and increased inundation risks during storm surges would be devastating both economically and environmentally. Moreover, the paleo-records may under-estimate the maximum possible future rates. Over the last few centuries, humanity has re-engineered the Earth in many aspects (e.g., atmospheric composition, land surface use, urbanization, water cycle, biodiversity) and created states not encountered over the past million years. The speed of change induced by humanity is unparalleled by the variability that is documented by the paleo-records of the last million years. Consequently, the response of the climate system may also exceed all rapid responses documented in these records, and sea level change exceeding those documented for the last million years cannot be excluded.

The absence of a scientific basis to exclude a large rapid LSL rise introduces the low-probability but extremely high-risk option of a significant and rapid LSL rise into the discussion of adaptation to LSL rise. Recently, several city managers have indicated that "early warnings" for a rapid LSL rise with lead times of five to fifteen years would provide actionable information for decision makers (e.g., Timothy Reeder, 2009, personal communication), and they have asked for the establishment of a decadal LSL forecasting service. Such a service would be comparable to the ongoing sky-watch for near-Earth objects, which addresses another low-probability/high-risk event.

In the next section, the societal and scientific challenges associated with adaptation to an uncertain sea level rise are described. Section 3 takes a novel approach to sea level rise based on Earth system properties as documented in the paleo-records. Section 4 discusses the consequences of a re-engineered planet for predictions of future system trajectories, and Section 5 asks whether this re-engineering introduces the possibility of environmental "black swans." Finally, Section 6 describes steps towards a sea level monitoring and forecasting service that could help to detect any emerging "black swan" with sufficient lead time allowing for efficient adaptation.

2. THE SOCIETAL AND SCIENTIFIC CHALLENGES

In many coastal areas with dense urban settlements, even a slow rise in LSL would increase the risks of extreme disasters caused by storm surges and hurricanes. A rapid increase of mean LSL of 50 cm or more over a few decades would cause significant problems for infrastructure in wide coastal areas. Policy makers face a trade-off between imposing today the very high costs of mitigation, adaptation, and coastal protection upon national economies and leaving the costs of major disasters for future generations. In handling this trade-off, society is challenged by a limited science support to inform the adaptation decisions: Recent assessments of 21st century LSL changes reveal large uncertainties in the plausible range of LSL trajectories, and these uncertainties are not communicated well. Decision makers do not get the support they need: "'*We can't make multi-billion dollar decisions based on the hypothetical*' says Rohit Aggarwala, the city's director of long-term planning and sustainability" [Wall Street Journal, September 11, 2009, "New York City Braces for Risk of Higher Seas"].

Science is challenged by the complexity of the Earth system and its inherent unpredictability, which make it difficult, if not impossible, to predict or usefully constrain the range of GSL rise and, even more so, LSL changes on century time scales. Moreover, humans have re-engineered the planet and changed major features of the Earth surface and the atmosphere, thus ruling out model-based extrapolations of past and current changes into the future (as applied by IPCC) as a reasonable approach. Unexpected changes due to rapid changes in ocean circulation and ice sheet mass balance can not be ruled out with certainty. Even without such large events, the range of plausible future sea level trajectories estimated on the basis of likely scenarios (Figure 1) turns out to be too large to be a useful basis for the planning of adaptation. The traditional reductionist approach, which assumes that by improving our understanding and numerical models, we will be able to improve the predictions, may not work (Harrison & Stainforth, 2009). New scientific approaches to decision support need to be developed.

3. WHAT DO THE PALEO RECORDS TELL US?

The more or less linear extrapolations of current knowledge used for the IPCC assessments seem to indicate that the 21st century GSL rise will not exceed 1 m (Figure 1). Other recent assessments limit the upper end for the 21st century GSL rise to about 2 m (e.g., Pfeffer et al., 2008). However, paleo-records show that the Earth system has the capability to produce larger century GSL rises (Figure 2). During the last several 100 Ka (Ka=1,000 years), the mean GSL rise was on the order of 1.5 m/century while maximum rates may have exceeded 3 m/century, and (since LSL change may exceed the global average by a factor of 1.5 or more even in tectonically stable locations) LSL changes of up to 4.5 m/century appear possible.

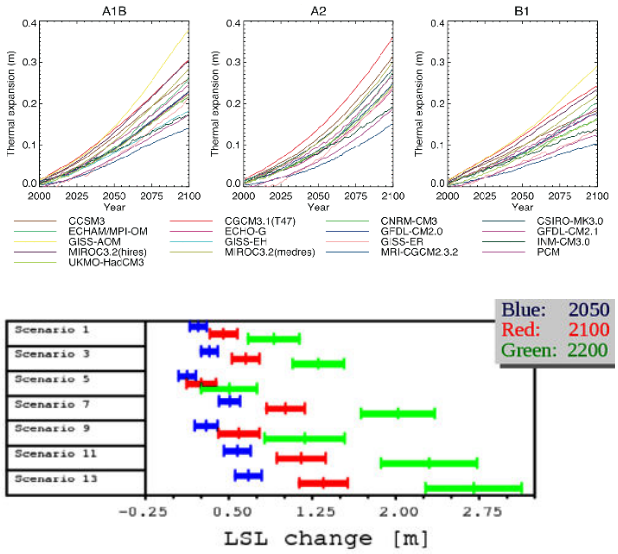

Figure 1: Top: IPCC Predictions for 21st century GSL rise (Meehl et al., 2007). Bottom: Range of plausible LSL trajectories for The Netherlands for different ice melt scenarios.

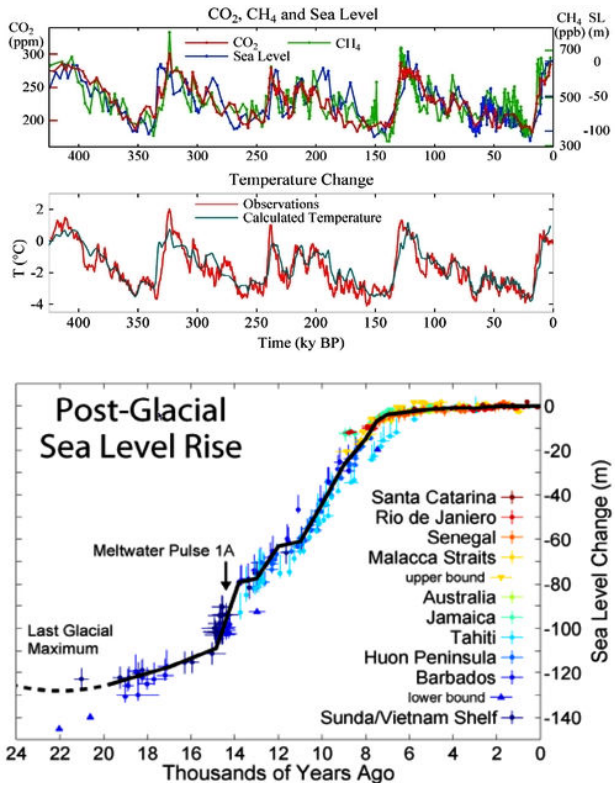

Figure 2: Paleo records of GSL and related parameters. Top: Global CO_2, CH_4, and GSL for the last 400 Ka. From Hansen et al. (2008). Bottom: GSL changes over the last 20 Ka. From http://en.wikipedia.org/wiki/File:Post-Glacial Sea Level.png.

4. THE CHALLENGE OF A RE-ENGINEERED PLANET

Over the last few centuries, humanity has re-engineered the Earth at an exceptional speed and created states not encountered over the past few million years. For example, the CO_2 concentration of 385 ppm observed in 2008 exceeds the previously occurring maximum of 300 ppm observed during the last 800 Ka by 65% of the total Glacial-Interglacial Range (GIR) of 130 ppm during this time, and using realistic emission scenarios, CO_2 values in excess of 400% of the GIR are predicted by the end of the 21st century (Figure 3), exceeding all changes recorded over the last million years (Karl et al., 2009). The speed of change is unparalleled, too: while during the last million years, maximum changes in CO_2 on the order of 100 ppm took place over thousands of years, humanity accomplished this in less than three centuries. Likewise, ocean acidity, land cover, and many other system parameters have been changed to values not encountered in the most recent several million years.

On a re-engineered planet, paleo-record may not have sampled the full range of possible future LSL rates. Under the unparalleled conditions created by humans, the response of the climate system may also exceed all rapid responses documented in the paleo-records. Rapid LSL changes unparalleled by those recorded in the paleo-records cannot be excluded.

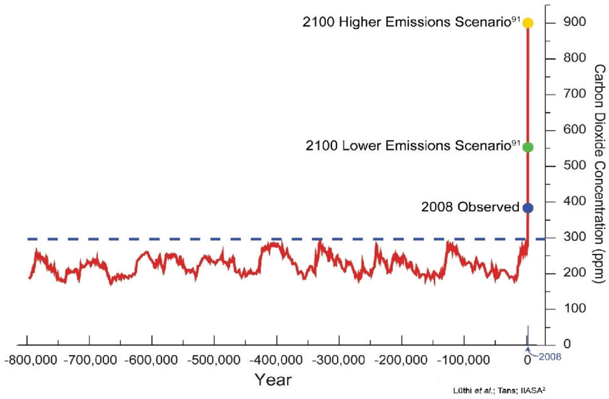

Figure 3: CO_2 changes over the last 800 Ka. From Karl et al. (2009).

5. IS THERE A "BLACK SWAN" WAITING FOR US?

The current wide-spread science approach to GSL and LSL changes lays the ground for a 'Black Swan' event. A Black Swan is an event
(1) that is an outlier, as it lies outside the realm of regular expectations;
(2) that carries an extreme impact;
(3) can be explained after the fact (Taleb, 2010).

The extremely stable GSL experienced by human civilizations during the last 7,000 years has led many to think that mean sea level changes slowly. Nothing occurring during the time of human civilizations indicates that a rapid GSL rise could happen, and even as scientists we tend to ignore the paleo-record or try to explain why the rapid variations that were common during most of the past million years could not happen today. Thus, many scientists consider a 21st century GSL rise of more than 1 m within the next 100 years as highly unlikely and more than 2 m as impossible. A 21st century GSL rise of more than 2 m would redraw the global coast lines. Today, with wide-spread built environment and crucial, potentially polluting infrastructure in coastal zones, rapid changes in coast lines and increased inundation risks during storm surges would be devastating both economically and environmentally. If such an GSL rise would happen, we can be sure that scientists after the fact would explain the event and classify it as predictable. The LSL Black Swan of the future could turn out to be a rather ugly bird - if it meets us unprepared.

6. TOWARDS SEALEVEL FORECASTING

In the face of the extremely high risk associated with a rapid LSL rise, the development of a sea level forecasting service that can detect in a timely manner the onset of an unlikely but not impossible rapid GSL rise and predict LSL trajectories for 10 to 20 years ahead in time would provide the early-warning function of a "smoke detector." Such a service is required in order to facilitate mitigation and adaptation where and when necessary. As demonstrated by, e.g., Velicogna (2009) Earth observation satellites, such as the satellite gravity mission GRACE, are capable of detecting major ice masses that enter a state of instability, and for these masses, predictions of their disintegration trajectories will be possible. Based on such disintegration predictions, LSL can be forecast with the same time horizon as for the ice sheets if a validated ice-ocean-solid-Earth model is available. Likewise, ocean observations will be able to detect the onset of major changes in ocean circulation and heat content affecting GSL and LSL, and validated atmosphere-ocean models will be able to forecast the further development on decadal time scales. Based on these modules, a modular, coupled, integrated system-wide modeling frame could be assembled and validated for a sea level forecasting system, which would allow the assessment of its predictive capabilities.

Key elements of such a LSL forecasting service would be a Global Cryosphere Watch (GCW) and models capable of assimilating GCW and other observations. In order to enable a timely "early warning" for a rapid sea level rise, continued sequences of satellite missions observing key parameters such as gravity (GRACE), ocean surface height, and ice sheet surface height are mandatory, and, considering the potential impact of a rapid LSL rise, these missions should have high priority in the development of the Global Earth Observation System (GEOSS).

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