Earth Observations as Decision Support for Adaptation and Mitigation Strategies in Response to Coastal Sea Level Rise

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Abstract - Local Sea Level (LSL) rise is among the major anticipated impacts of future global warming. 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. Predictions of future LSL trajectories with reliable estimates of uncertainties are a crucial input to risk and vulnerability assessments in support of informed decisions. Current aleatory uncertainties in observations related to past and current LSL variations combined with epistemic uncertainties in some of the global, regional and local processes forcing LSL changes produce a large range of plausible future LSL trajectories and weak estimates of uncertainties. Therefore, policy makers often lack sound scientific support for the development of reasonable mitigation and adaptation strategies in the coastal zone. Additional spaceborne and in situ observations are needed in order to improve decision support by reducing the uncertainties in LSL predictions.

Key words: Sea level rise, Climate change impact, Risk assessment, Decision support

1. INTRODUCTION

Global warming is likely to lead to a significant rise in Global Sea Level (GSL) over the next century and beyond, with potentially devastating impacts on coastal cities and settlements (Rowley et al., 2007). In many locations, Local Sea Level (LSL) changes deviate significantly from GSL changes, and in some locations, LSL rise will exceed the global average by a factor of two or more. Together with changing frequencies of storm surges, socio-economic change and coastal defence degradation over time, LSL changes are likely to alter patterns of hazard and exposure, and hence risk, and these changes potentially will lead to extreme disasters in coastal areas with dense urban settlements. The "*displacement through flooding and tropical storm activity of up to 332 million people in coastal and low-lying areas*" is among the threats to human development identified by Watkins & HDR Team (2007). Estimates for East Asia show that a projected one-meter rise in sea levels could lead to a two percent loss of Gross Domestic Product (World Bank, 2008), and loss estimates for single major disasters due to storm surges and hurricanes hitting urban areas are in excess of $100 billion. Today's planning decisions will have long-term implications for coastal sustainability and resilience with a trade-off between the costs spent today on mitigation and adaptation and the costs of disasters to be born by future generations. Considering the high costs of coastal protection or adaptation and of potential disasters caused by coastal hazard, both over and under-protection/adaptation can be very costly and significantly impact the national economy. Adaptation may require relocation of settlements 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 (e.g., Hulme et al., 2002; Plag et al., 2006; CCSP, 2008; Katsman et al., 2008), and some common conclusions concerning the obstacles and potential improvements have emerged (see, e.g., Chapter 6 in CCSP, 2008). Common to all is the conclusion that a *better understanding of the uncertainties of predictions for the various forcing functions*, including validated Probability Density Functions (PDFs), is mandatory for improved decision support.

In the next Section, first an account of the forcing processes for LSL variations is provided. In Section 3, a local approach to the assessment of the range of plausible future LSL trajectories is described based on an analysis of the LSL forcing processes. This approach is then used to classify and, where possible, quantify the current uncertainties (Section 4). Finally, observational gaps are identified that contribute significantly to the current uncertainties.

2. LSL FORCING PROCESSES

LSL is defined here as the distance between the sea surface and the ocean bottom:

$$h(\lambda,\theta,t) = \begin{cases} r_1(\lambda,\theta,t) - r_0(\lambda,\theta,t) & : \text{ in the ocean} \\ 0 & : \text{ on land ,} \end{cases} \qquad (1)$$

where r_0 and r_1 are the geocentric positions of the sea floor and sea level, respectively (Plag, 2006; Mitrovica et al., 2009). λ and θ are the geographical longitude and latitude, respectively, and t is time. Variations $\xi(t) = h(t) - h_0$ of LSL are the result of variations in r_0 or r_1, or both. LSL is the quantity that is directly related to the potential impact of global and regional changes in climate and sea level in a given coastal area. At any location, LSL is the result of a number of Earth-system processes including climate, geodynamics, mass transport in the global water cycle, and, more recently, anthropogenic activities, as well as interactions between these processes. These forcing processes act on local, regional, and global scales, and on a wide range of time scales. For the assessment of impacts, the combined effects of the high-frequency and low-frequency LSL variations are important. However, it is helpful to consider the high-frequency and low-frequency parts separately.

The *high-frequency* part of LSL variations can be described by:

$$\xi_{\rm hf}(t) = \xi_{\rm wa}(t) + \xi_{\rm ti}(t) + \xi_{\rm at}(t) + \xi_{\rm sei}(t) + \xi_{\rm tsu}(t), \qquad (2)$$

and accounts for waves, tides (up to monthly periods), seiches, tsunamis, and atmospherically driven variations on time scales of hours to several weeks.

An equation relating the global, regional and local forcing processes to low-frequency LSL variations can be written as:

$$\xi_{\rm lf}(\vec{x},t) \;=\; S(\vec{x},t) + C(\vec{x},t) + F(\vec{x},t) + A(\vec{x},t) +$$

$$I(\vec{x},t) + G(\vec{x},t) + T(\vec{x},t) + P(\vec{x})(t-t_0) + V_0(\vec{x})(t-t_0) + \delta V(\vec{x},t) \quad (3)$$

where t_0 is an arbitrary time origin (Plag, 2006). The processes included in eq. (3) are S: steric changes, C: ocean circulation, F: freshening due to melting of sea and land ice, A: atmospheric forcing, I: mass changes in the large ice sheets, G: mass changes in the continental glaciers, T: mass changes in the terrestrial hydrosphere, P: post-glacial rebound, V_0: secular vertical land motion others than postglacial rebound, δV: non-linear vertical land motion (for details, see Plag, 2006). Importantly, those processes, which involve redistribution of mass in the water cycle all are associated with viscoelastic-gravitational effects on LSL, leading to very distinct spatial and temporal patterns of LSL variations. Consequently, LSL changes caused by mass redistribution in the global water cycle depend crucially on where the mass redistribution takes place. The governing equation that links present and past mass redistribution to LSL variations was first introduced by Farrell & Clark (1976) and is denoted here as the mass-LSL equation. This equation has been used extensively for studies of post-glacial sea level (see, e.g., Mitrovica & Milne, 2003, and the reference therein). The disintegration of the last great ice sheets produced a distinct and time-variable spatial pattern in LSL. The elastic response of the Earth to present-day changes in the cryosphere can be expected to produce similar spatial variability. Nevertheless, using the same equation to describe the relation between present-day mass changes and LSL has been restricted to a few examples (e.g., Plag & Jüttner, 2001; Mitrovica et al., 2001; Plag, 2006; Mitrovica et al., 2009).

Major mass redistribution in the global water cycle can result from significant melting of the Antarctic Ice Sheet (AIS) and Greenland Ice Sheet (GIS). For these two large ice sheets, global LSL fingerprints have been computed by assuming a unit melting rate across the complete area of the ice sheet and a purely elastic response of the solid Earth (Plag & Jüttner, 2001; Mitrovica et al., 2001). From these fingerprint function, Admittance Functions (AFs) can be computed by normalizing the fingerprint by the corresponding GSL change. With these AFs, a predicted GSL rise can be converted into a LSL contribution at a specific location. However, the AFs for the AIS and GIS computed by Plag & Jüttner (2001) exhibit considerably larger spatial variability than those computed by Mitrovica et al. (2001, 2009) and Vermeersen et al. (2008, personnel com.). The cause for the difference in the AFs can be in the Earth model, computation of the system response (Green's function), the convolution, and the numerical solution of the integral mass-LSL equation itself. Unfortunately, due to the absence of modern observations close to sufficiently large and rapidly changing ice masses, a comparison of near-field concurrent LSL changes to predictions has not been possible so far. First observations are just emerging from the vicinity of rapidly melting ice sheets in Greenland and Svalbard (Khan et al., 2007; Kierulf et al., 2009).

3. PLAUSIBLE FUTURE LSL TRAJECTORIES

Earth system models available today are not capable of modeling all LSL forcing processes and predicting LSL changes, for example, as a function of emission scenarios. A simple, precautionary approach proposed by Hulme et al. (2002) would take the GSL scenarios provided in the Fourth Assessment Report of the IPCC (AR4) and multiply them by 1.5 in order to account for potential local to regional amplifications. However, this approach might easily lead to estimates far too large or too small since it is not allowing for the spatial variability of all the relevant sub-global processes. Recent assessments (e.g., Plag et al., 2006; Katsman et al., 2008) have applied modified versions of eq. (3). For some forcing processes, secular trends can be determined from observations and extrapolated into the future. For other forcings, models are available that can be used in ensemble studies of future developments. For some processes, our knowledge is limited and a wide range of scenarios has to be considered, similar to the approach taken for the assessment of future climate change (e.g., Meehl et al., 2007).

Most recent assessments indicate that the high-end of the range of plausible LSL trajectories for 2100 is in the 1 to 2 meter range above the current level, particularly in areas where subsidence contributes. Following the IPCC AR4 (Meehl et al., 2007), most of these assessments do not assume significant AIS or GIS contributions. Recent research results (e.g., Zwally et al., 2002; Pfeffer et al., 2008), however, indicate the possibility of a dynamic response of these ice sheets to global warming. Current ice models cannot provide reliable predictions of such a dynamic response (Libcomb et al., 2009), and a major uncertainty for sea level predictions is associated with the contribution from ice sheets.

4. UNCERTAINTIES

A key question raised in the frame of recent assessments of LSL rise is whether there is a global relationship between the PDF for global temperature and a PDF for GSL rise (e.g., Rahmstorf, 2007). Even if such a relationship could be determined for the past, based on a GSL sensitivity to global average temperature, it has to be doubted that this relationship also would apply to the future. Both, LSL and GSL are the result of many processes with different spatial and temporal scales. An empirically determined relationship between PDFs for global temperature and GSL would only be applicable to the future if the mix of processes contributing to past GSL would be the same in the future. This is highly unlikely. Moreover, each forcing process is associated with its own PDF, which in most cases is geographically and temporally variable. The combination of the PDFs of the individual forcing processes to the PDF for LSL is complicated by the fact that our knowledge of the individual processes, both for past and future, is associated with different types of uncertainties (Tab. 1). Some of the contributions in eq. (3) can be derived directly from observations, while for others such observations are not available.

An empirical version of the low-frequency LSL equation represents LSL variation as the sum of four contributions resulting from oceanographic processes, mass exchange with other reservoirs in the water cycle, vertical land motion, and atmospheric processes. In many cases, this empirical relation can be used to determine PDFs for the four terms and to map the range of future LSL trajectories. The quantitative understanding of the uncertainties to a large extent is based on analyses of recent LSL variations. Observations of past LSL changes and relevant forcings have been used to understand and quantify the contributions of steric changes, atmospheric forcing, mass redistribution, and vertical land motion to LSL variations locally, regionally, and globally (e.g., Bindoff et al., 2007). Concerning the four empirical forcing terms, it is pointed out that variations in the low-frequency atmospheric forcing are mainly of cyclic multidecadal nature and can add on the order of ± 100 mm to the LSL

Table 1. Five types of uncertainties and their relevance to LSL forcing processes. Types of uncertainties are from Manning & Petit (2003).

Uncertainty	Class	LSL forcing process
Incomplete or imperfect observations	aleatory	vertical land motion, reference frame, oceanographic observations;
Incomplete conceptual framework	epistemic	yes with respect to climate system; no with respect to mass-LSL relation;
Inaccurate description of known processes	epistemic	one-dimensional models, incomplete mass redistribution, gravitationally inconsistent models, programming errors;
Chaos	epistemic	yes with respect to climate system; no for mass-LSL relation;
Lack of predictability	epistemic	ice sheet behavior, mass exchange, ocean warming, circulation changes.

changes. In some locations, current vertical land motion is observed by GPS and thus known with respect to the Center of Mass of the Earth system (CM) with an uncertainty on the order of ± 1 mm/yr. Uncertainties of the predictions result from difficulties to separate transient contributions from secular motion that could be extrapolated. The PDF for vertical land motion therefore depends strongly on local conditions. Although the contribution of steric variations to GSL are most likely on the order of 2 to 4 mm/yr, spatial variability can be on the same order or larger, introducing a considerable spread in the PDF of this term. Moreover, ocean circulation changes and their impact on sea surface topography add to this.

The contribution to secular LSL changes due to mass redistribution in the global water cycle is difficult to assess. For postglacial rebound due to the past large mass relocation during the ice ages, geophysical models predict the present-day changes in LSL with an uncertainty on the order of ± 2 mm/yr for areas with the largest signals. The main sources for current and future mass exchange with the ocean are the large ice sheet, the continental glaciers, and continental water storage in groundwater, lakes, and reservoirs (e.g., Bindoff et al., 2007). The total change of ocean mass over the last 40 years is estimated to be in the range of -0.4 to 1.1 mm/yr in GSL rise. LSL variations deviate significantly from these GSL changes. The largest single contribution to ocean mass changes can potentially come from the AIS and GIS. Unfortunately, this is also the most uncertain contribution with large aleatory uncertainties attached to measurements of current changes. Major epistemic uncertainties are in the response of the large ice sheets to global warming (Libcomb et al., 2009), and their contribution to a GSL rise is highly uncertain (Pfeffer et al., 2008). A PDF for this contribution will have to take into account the rapidly developing knowledge about these potential dynamic effects. Once the global contribution of a large ice sheets or glacier is known, in principle, the local contribution can be computed by multiplication with the appropriate AF discussed above. Unfortunately, there are large inter-model differences, which may be due to a combination of several causes. These model discrepancies fall into the third group of uncertainties (Tab. 1), i.e., inaccurate description of known processes. For the contribution of glaciers, a complication results from the fact that each glaciated region is associated with a specific AF, thus requiring prediction of mass changes for each region.

5. REDUCING THE UNCERTAINTIES

Based on the previous discussion, we can list the following challenges, gaps, and steps towards improvements.

Understand current LSL changes: In many coastal urban areas, LSL is not sufficiently monitored, particularly in developing countries. Additional tide gauges, preferably co-located with GPS stations, are urgently needed to get reliable measurements of how LSL is changing in these high-risk areas. Satellite altimetry provides observations of sea surface changes, which in coastal areas are inherently more uncertain than in the open ocean. In order to convert these observations into LSL variations, information on vertical land motions is required. Reducing the uncertainties in the tie between the origin of the geodetic reference frame and CM would reduce the aleatory uncertainties of currently observations of vertical land motion. Observations of LSL variation, vertical land motion, and gravity changes in areas near to rapidly melting coastal glaciers should have high priority as they would be very valuable for validation of the mass-LSL equation.

Current LSL forcing: Considerable gaps exist in our knowledge of current LSL forcing for most contributions, including steric changes, mass redistribution in the water cycle, and vertical land motion. Coastal observations of salinity, temperature, and currents together with improved ocean models are needed to reduce the uncertainty in the steric forcing. The lack of detailed global models of mass redistribution in the global water cycle contributes significantly to the overall uncertainties. Inversion of geodetic observations of changes in Earth's shape, gravity field and rotation can help to reduce the uncertainties in mass relocation, particularly if these observations are assimilated into water cycle models. Models of vertical land motion induced by past and present mass distributions would help to separate this transient contribution from secular tectonic motions that could be extrapolated.

Predictions: For LSL predictions improved models of future mass changes in land water storage (with sufficient spatial resolution), individual glaciers, and ice sheets would be a major contribution to reducing the uncertainties in many locations. A key contribution is potentially due to the GIS and AIS, and their responses to global warming needs to be monitored closely, and models with predictive capabilities need to be developed. Likewise, better estimates of the spatial variability of thermal expansion are need.

6. CONCLUSIONS

Recent assessments of future LSL changes have shown that a local approach based on eq. (3) is a reasonable approach for mapping the range of plausible future LSL trajectories. However, the currently large uncertainties in the predictions of a number of forcing processes greatly reduce the value of the LSL assessments for policy making. A major coordinated efforts in observation, modeling, and validation is needed to establish reliable PDFs for all main forcing processes and to reduce the uncertainties to a level serving the purpose of decision support.

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