Observations as decision support for coastal management in response to local sea level changes

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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. Thus, scientific support for policy makers aiming at reasonable coastal zone policies and mitigation and adaptation strategies is limited. Additional spaceborne and in situ observations are needed in order to improve decision support by reducing the uncertainties in LSL predictions through better estimates of current trends and improved predictive capabilities of relevant models.

1. Introduction

The goal of this white paper is to show that the large uncertainties in projections of Local Sea Level (LSL, sometimes called relative sea level) rise over the next century could be reduced significantly with a coordinated interdisciplinary effort in observation, analysis, and modeling of the forcing processes for LSL variations. LSL rise is one of the anticipated major impacts of future global warming requiring expensive coastal protection measures and/or costly adaptation strategies. The very existence of small island states may be at jeopardy from LSL rise in conjunction with short-term disturbances. Particularly if combined with land subsidence, an increase of sea-surface height may lead to major inundation in many coastal areas. A long-term increase in LSL will also change the risks associated with storm surges and hurricanes, leading to potentially extreme disasters in coastal areas with dense urban settlements. Loss estimates for single major disasters due to storm surges and hurricanes hitting urban areas, for example, in North America or East Asia, are in excess of $100 billion. Today's planning decisions will have long-term implications for coastal sustainability and decision makers face a trade-off between burdening national economies today with very high costs of coastal protection, mitigation and adaptation and leaving the costs of major disasters to be borne by future generations. Informed decisions require predictions of the plausible range of future LSL rise with reliable estimates of uncertainties as inputs for risk and vulnerability assessments. Secular changes in LSL are the result of a location-dependent mix of factors including ocean temperature and salinity changes, ocean and atmospheric circulation changes, mass exchange of the ocean with terrestrial water storage and the cryosphere, vertical land motion, and geomorphology and bathymetry of coastal estuaries and lagoons. Recent assessments of LSL changes for several coastal areas, including the Dutch Coast, the Northern Adriatic, and the southern coast of the USA showed that the current aleatory (statistical) uncertainties in observations relevant to past and current LSL changes combined with epistemic (systematic) uncertainties in some of the LSL forcing functions produce a large range of plausible future LSL trajectories. In particular, the interaction between ocean and ice as observed over the last decade points to a large uncertainty in the response of ice sheets to climate change and their contribution to LSL. Coupling the large range of plausible sea level trajectories with uncertainties about inundation risks and incomplete environmental, social, and economic data, as is the case in many developing nations, leads to considerable uncertainties in risk and vulnerability assessments. Thus, policy and decision makers who look to a sound scientific basis to determine reasonable coastal zone policies and mitigation and adaptation strategies lack the security of well bounded information.

It is our goal to identify observation and modeling gaps that contribute to the large uncertainties in LSL projections and to propose steps towards closing these gaps. A lack of observations hampers both the understanding of past LSL variations and the development and validation of models required for predictions of future LSL trajectories. Insufficiently validated models and a lack of sufficiently comprehensive models introduces unnecessary uncertainties or reduces the value of model studies required to map the full range of plausible future sea level trajectories. In the next section, we give an account of the forcing processes for LSL variations. In Section 3, we review the best practice in determining the range of plausible future LSL trajectories and in Section 4, we classify and, where possible, quantify the current uncertainties. Finally, in Section 5 we identify observation and modeling gaps that contribute significantly to the current uncertainties and suggest actions to close these gaps.

2. Forcing processes for LSL changes

LSL is defined here as the distance between the sea surface and the surface of the solid Earth. Thus, changes in LSL can arise from changes in the vertical position of the sea surface and the surface of the solid Earth. In coastal areas, LSL 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 and energy transport in the global water and energy cycle, deformations of the solid Earth to internal (geodynamic) and external process, and, more recently, anthropogenic activities, as well as interactions between these processes. These forcing processes act on local, regional, and global spatial scales, and on a wide range of time scales. In a local approach, LSL variations can be described as the sum of contributions from various forcing processes. However, the relative weight of the individual processes depends on the time scale considered. For the assessment of impacts, the combined effects of high-frequency and low-frequency LSL variations are important. For our discussion, we consider high-frequency and low-frequency LSL variations separately, and we separate these two parts at a period of approximately two months. At most locations, these two parts can simply be added, with little dynamic interactions, except for limited areas of resonance. The forcing of the high-frequency part includes waves, tides, atmospheric forcing (including storm surges), and tsunamis. The low-frequency forcing includes long-period tides, steric expansion, ocean currents, freshening due to melting of sea and land ice, atmospheric forcing, mass changes in the large ice sheets, mass changes in the continental glaciers, mass changes in the terrestrial hydrosphere, post-glacial rebound, secular vertical land motion other than postglacial rebound, and non-linear vertical land motion (Plag, 2006a).

It is important to note that processes involving 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 caused by these processes (e.g., Farrell and Clark, 1976). In particular, LSL will fall close to a melting ice mass due to reduced gravitational attraction from the vanishing ice mass and an elastic rebound of the crust under the melting ice, and LSL will rise more than the global average in the far-field. In order to emphasize the importance of the fundamental relationship between any mass transport in the global water cycle and the LSL, we consider the case where the Greenland Ice Sheet (GIS) melts while the Antarctic Ice Sheet (AIS) increases with the two changes being exactly in balance. This mass movement will not induce any Global Sea Level (GSL) change since the mass and volume of the ocean are constant, but LSL will fall significantly over large regions of the northern hemisphere and increase over large parts of the southern oceans. This complex relation between LSL and ocean mass changes has to be accounted for when considering GSL and LSL changes (as reconfirmed by Mitrovica et al., 2009). The so-called fingerprint or admittance functions, which describe the LSL response to a unit change in a glacier or ice sheet, can be used to derive LSL changes for known mass changes in the glacier or ice sheet.

An empirical version of the low-frequency LSL equation represents LSL variation as the sum of four contributions resulting from (1) oceanographic processes, (2) mass exchange with other reservoirs in the water cycle, (3) vertical land motion, and (4) atmospheric processes (Plag et al., 2006). Mass redistribution on the Earth surface loads and deforms the solid Earth and thus contributes to vertical land motion. Close to significant mass changes, the vertical displacement of the solid Earth's surface can be the dominant contribution to LSL changes. For the analysis of past LSL variations documented by oceanographic, atmospheric, and geodetic observations, it may be appropriate to include the mass-induced displacements of the Earth's surface in the vertical land motion term, while for projections of future LSL trajectories, it may be more appropriate to include the deformation in the mass term.

3. Best practices in LSL predictions

The goal of recent assessments of LSL changes for a given coastal area has been to provide realistic ranges of plausible future LSL trajectories as a basis for risk and vulnerability assessments and as input for policy and decision making with respect to coastal zone development, mitigation, and adaptation. The most useful result with respect to LSL would be an assessment of the range of plausible LSL trajectories associated with a Probability Density Function (PDF). Most important for planning of adaptation and coastal protection is the high end of the range, which represents high-risk, low-probability events.

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. Therefore, different methodologies have been used in recent assessments. A simple, precautionary approach proposed by Hulme et al. (2002) would take the GSL scenarios provided in, for example, the Fourth IPCC Assessment Report (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 forcing processes.

In order to get more accurate local estimates, recent assessments have applied a local approach in which predictions of the LSL contributions due to the individual forcing processes are summed. For some of the processes, such as secular vertical land motions, observations may be available, which to a certain extent can be extrapolated. Other contributions, such as the steric contribution, can be studied based on global and regional climate models, and ensemble studies can be used to derive PDFs for such contributions. For other processes, such as the contribution from the large ice sheets, no models exists that can reliably predict the response of these ice sheets to global warming (Lipscomb et al., 2009), and a scenario approach can be used to assess the potential LSL contribution for a wide range of plausible forcing scenarios, similar to the approach taken for the assessment of future climate change (see, e.g., Meehl et al., 2007). Using this combined approach, a set of plausible LSL projections can be determined based on the understanding of the past LSL changes in a given location. Using realistic estimates for the future contribution of thermal expansion, the cryosphere, terrestrial water storage, and vertical land motion, the uncertainties of the resulting LSL trajectories can be derived. This approach has been used, for example, for recent assessments of the LSL rise scenario for Venice (Plag et al., 2006), and the study of high-end scenarios for the Dutch Coast (Katsman et al., 2008).

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 (see, e.g., Rahmstorf, 2007). Even if such a relationship could be determined for the past, it has to be doubted that this relationship also would apply to the future. Both LSL and GSL (i.e., the spatial average of LSL) 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. Therefore, an experimentally determined PDF for GSL as function of the PDF for global temperature cannot be extrapolated into the future. Even if such a PDF for GSL could be established, it would not be very helpful for local or regional studies. The individual LSL forcing processes listed above are associated with their specific fingerprints with characteristic spatial and temporal scales. Each process is associated with its own geographically and temporally variable PDF. 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 the past and future, is associated with different types of uncertainties.

4. Epistemic and Aleatory Uncertainties

Our knowledge of global change processes is associated with different types of uncertainties, depending on the forcing process and the source of knowledge (Table 1). Some of the contributions to LSL changes can be derived directly from observations, while for others such observations are not available. In the case of LSL, 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. In most locations, the interval best covered by relevant observations extends from approximately 1960 to present. For that period, both steric observations and meteorological observations are available globally and have been studied extensively. Most studies of past LSL trends use the monthly (or annual) mean LSL data made available by the Permanent Service for Mean Sea Level (PSMSL) hosted by the Proudman Oceanographic Laboratory, Liverpool (e.g., Woodworth and Player, 2003). The spatial distribution of tide gauges is rather inhomogeneous with high station densities restricted to a few regions such as the European coasts, North America, and Japan, particularly if stations with longer records are considered. Thus, for many areas, large uncertainties result from a lack of past LSL observations as well as a lack of other required observations. Satellite altimetry provides sea surface height changes, and conversion of those to LSL changes requires measurements of vertical land motion.

Table 1: Types of uncertainties associated with global change processes and their relevance to LSL forcings. Types of uncertainties are from Manning and Petit (2003).

Uncertainty	Class	LSL forcing process
Incomplete or imperfect observations	Aleatory	vertical land motion, reference frame, oceanographic observations
Incomplete conceptual framework	Epistemic	with respect to climate system: Yes; with respect to mass-LSL relation: No
Inaccurate description of known processes	Epistemic	one-dimensional models, incomplete mass redistribution, gravitationally inconsistent models, programming errors;
Chaos	Epistemic	With respect to climate system (including ocean circulation): Yes; for mass-LSL relation: No;
Lack of predictability	Epistemic	ice sheet response to warming, mass exchange, ocean warming, circulation changes

Concerning the four empirical forcing terms mentioned above, we emphasize that variations in the low-frequency atmospheric forcing are mainly of a cyclic multi-decadal nature and can add on the order of ±100 mm to the LSL changes (Plag, 2006b). 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 in the order of ±1 mm/yr. It is important to acknowledge that for LSL assessments vertical land motion needs to be known with respect to the CM, not relative to other points on the Earth's surface. The main part of the uncertainty in vertical rates is attributed to the relation of the origin of the global geodetic reference frame to the CM (Blewitt et al., 2006). Uncertainties in the predictions of future vertical land motion result mainly from difficulties in separating 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 in the order of 1 to 4 mm/yr, spatial variability can be in 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 can add to this. The contribution to secular LSL changes that is most difficult to assess arises from mass transport in the global water cycle. For postglacial rebound resulting from the large past mass relocation during the ice ages and afterwards, geophysical models predict the present-day changes in LSL with an uncertainty in the order of ±2 mm/yr for areas with the largest signals (i.e., the areas glaciated during the last ice ages, where present-day LSL changes are in the order of 10 mm/yr).

In summary, we can state that in a world with more or less linear extrapolations of today's rates superimposed by climate impact as assessed by the IPCC assessment, the main contributions to the overall uncertainty in LSL projections are associated with the steric contribution resulting from thermal expansion and vertical land motion. For scenarios with accelerated melting of ice (see, e.g., Meier et al., 2007, Pfeffer et al., 2008), the individual contributions of the ice sheets and glaciers to the overall uncertainty are all in the same order as those of the steric contribution and vertical land motion.

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 (see, e.g., Church et al., 2001; Bindoff et al., 2007; Meehl et al., 2007). The total change of ocean mass over the last 40 years is estimated to have caused a 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 (Lipscomb et al., 2009), in particular, the interaction between ocean and ice as observed over the last decade. Therefore, 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 sheet or glacier is known, in principle, the local contribution can be computed by multiplication with the appropriate admittance function. 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 identified by Manning and Petit (2003), i.e., inaccurate description of known processes. For the contribution of glaciers, a complication results from the fact that each glacier-region is associated with a specific LSL-fingerprint.

5. Reducing the uncertainties by closing observational gaps

Recent assessments of future LSL changes have shown that a local approach summing the projections of LSL changes due to the individual forcing processes 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 effort in observation, modeling, and validation is needed to establish reliable PDFs for all main forcing processes and to reduce the uncertainties in our understanding of current LSL changes and their forcing, as well as in predictions of future changes, to a level serving the purpose of decision support.

Understand current LSL changes: In many coastal areas, including urban coastal settlements and mega cities, LSL is not sufficiently monitored. Particularly in many developing countries, tide gauges have not been well maintained and those that have been are few and far between. Additional tide gauges, preferably co-located with GNSS stations, are urgently needed to get reliable measurements of how LSL is changing, particularly in the high-risk areas of coastal mega cities. Satellite altimetry observations provide synoptic coverage and finely resolved determinations of sea surface height changes at global and regional scales, and these observations are pivotal for monitoring and understand LSL and GSL changes. However, in coastal areas these observations are inherently more uncertain than in the open ocean and need to be complemented by in situ observations. Moreover, propagation of steric changes in the deep ocean into coastal areas is not well understood, and improved models are needed in order to estimate the effect of observed deep ocean changes in coastal areas. 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 the CM would significantly reduce the aleatory uncertainties of current observations of vertical land motion.

Current LSL forcing: Despite considerable progress during the last decades, 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. In particular, an improved understanding of how steric variations in the deep ocean propagate into coastal areas is needed.. 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 ensuring mass conservation on a global scale. In many locations, either subsidence contributes significantly to LSL increase, or land uplift reduces LSL rise considerably. However, observations of vertical land motion in coastal areas are still sparse and in many urban areas absent, particularly in developing countries. Observations of vertical land motion from a combination of GNSS stations and InSAR are needed to map the spatial variability of this contribution to LSL changes. 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.

Measurements of current trends in ice sheets and glaciers are important observations both as constraints for model development and validation, and for identifying the contributions to current LSL changes. Observations of LSL variation, vertical land motion, and gravity changes in areas near to rapidly melting coastal glaciers (e.g., in Greenland, Alaska, Svalbard, and parts of Antarctica) should have high priority as they would be very valuable for validation of the mass-LSL equation.

Predictions: Some of the uncertainties in forcing processes contributing to LSL changes are of epistemic nature and require considerable research and model development. For the contributions of steric expansion, ocean circulation, and atmospheric circulation to LSL, the large uncertainties in spatial variability need to be reduced (e.g., Stammer, 2008) and considerable effort is being made to quantify the uncertainties through ensemble studies and to improve predictions through model development. 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 Greenland and Antarctic ice sheets, and their responses to global warming needs to be monitored closely. Recently, the lack of models that can predict the response of the ice sheets to global warming has been emphasized, and efforts are under way to address this gap by developing models with predictive capabilities (Lipscomb et al., 2009). Likewise, better estimates of the spatial variability of thermal expansion are needed, for example from ensemble studies. The use of these predictive models in scenario-based assessments would help to better determine the range of plausible LSL trajectories, including better founded PDFs, as improved support to decision-makers.

6. Conclusions

Although improved observations and research likely will lead to a better understanding of the processes forcing sea level changes and to better models, it has to be doubted that the predictive capabilities of models can be improved in the near future to allow for reliable LSL predictions on time scales of several decades to several centuries. The complexity of the Earth system processes forcing LSL changes and the lack of predictability of some of the processes make it difficult to predict GSL rise and, even more so, LSL changes over the next 100 to 200 years. The risk of rapid changes in ocean circulation and ice sheet mass balance introduces the possibility of unexpected changes. Therefore, monitoring of the relevant processes (in particular, ice sheet mass balance and ocean circulation) and development of a forecasting service on realistic time scales is crucial as decision support. Forecasting and "early warning" for LSL rise would have to aim at decadal time scales, giving coastal managers sufficient time to react if the onset of rapid changes would require an immediate response. The social, environmental, and economic risks associated with potentially large and rapid LSL changes are enormous. Therefore, in the light of the current uncertainties and the unpredictable nature of some of the forcing processes for LSL changes, the focus of scientific decision support may have to shift from projections of LSL trajectories on century time scales to the development of models and monitoring systems for a forecasting service on decadal time scales.

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