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Toward an Interannual to Decadal Local Sea Level Forecasting Service

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1. Introduction

Climate change 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, Edwards 2008, Hallegatte 2012, Hallegatte *et al.* 2013, Horton *et al.* 2014). The societal and economic impacts would be felt globally. Recent successive events show that the costs of single sea-level related disasters are increasing and exceeding $100 Billion. In many urban coasts, an accelerated Local Sea Level (LSL) rise is presently causing mounting adaptation costs (*e.g.*, Atkinson *et al.* 2013). The recent extreme events (*e.g.*, tropical cyclones Katrina, Sandy, and Haiyan) are demonstrating the high risks for urban coasts associated with storm surges and hurricanes. Spatial variability in LSL (*e.g.*, Plag 2006, Ezer 2013) will amplify any increase in GSL on regional scales. Acceleration in LSL rise is also spatially variable, and some regions already exhibit significant non-linear changes (*e.g.*, at the U.S. East Coast, Sallenger et al. 2012, Ezer *et al.* 2013, Kopp 2013). In a recent report of the National Research Council's Committee on Abrupt Climate Change, the risk for rapid climate change impacts is emphasized (NRC 2013). In particular, the uncertain response of the large ice sheet to climate change (*e.g.*, Little *et al.* 2013; see also the discussion in Plag and Jules-Plag 2013, and the reference therein) introduces the possibility of a rapid GSL rise. The rate of change in global temperature observed in the last, and projected for the current century is much greater than those documented for many past millennia (Marcott *et al.* 2013), and the projected changes classify as “abrupt changes.” Under these conditions, rapid sea level changes cannot be excluded.

Projections of GSL and LSL on century time scales are highly uncertain, and recent risk assessments demonstrate that presently future LSL variations are not predictable on century time scales (Plag and Jules-Plag 2013, and the reference therein). The large uncertainty in the plausible range of LSL trajectories and their Probability Density Functions (PDFs) reduces the value of these long-term assessments for risk management. Even the upper end of the range of plausible future LSL trajectories is highly uncertain (Horten *et al.* 2014) . Importantly, the trajectories do not account for the risk of abrupt climate change. The range of plausible GSL trajectories resulting from the still unpredictable response of the large ice sheets to climate change is often displayed for GSL trajectories at the end of the 21st Century (Figure 1), giving the false impression that the large range of plausible trajectories can only develop on century time scales. However, there is no scientific basis to exclude rapid contributions from the ice sheets on decadal to multi-decadal time scales, opening the

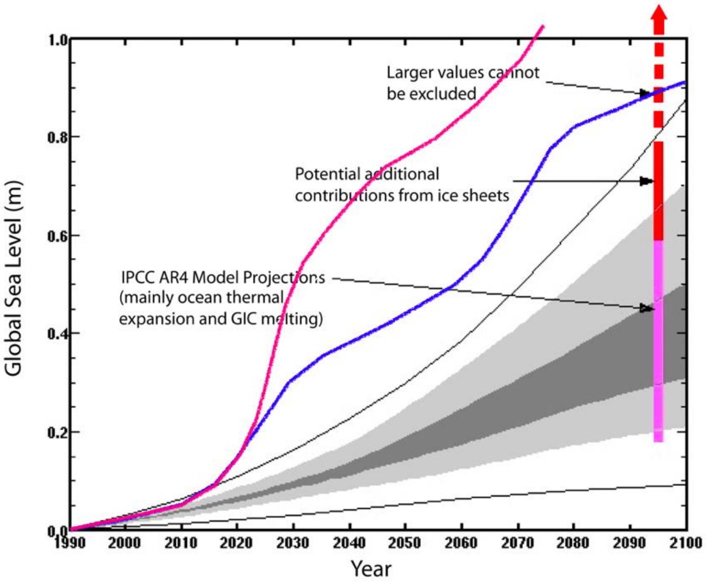

Fig. 1 Plausible 21st Century trajectories of GSL cover a wide range at the end of the present century, with possibly much higher trajectories indicated for the later part of the 21st Century (red arrow). However, rapid increases caused by rapid melting of parts of the large ice sheets are possible over the next decades, and trajectories like the red and blue one cannot be excluded. Modified from Church *et al.* (2010).

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possibility for low-probability, high impact rapid increases in GSL already in the near future. Such a rapid rise would have devastating consequences for the growing urban coasts, including coastal mega cities. In fact, observations of the ice sheets during the last 10 years have repeatedly surprised glaciologists and earth scientists with large and accelerating melting rates (Velicogna and Wahr 2005, 2006) that exceeded what was considered likely, or even possible, a few years earlier.

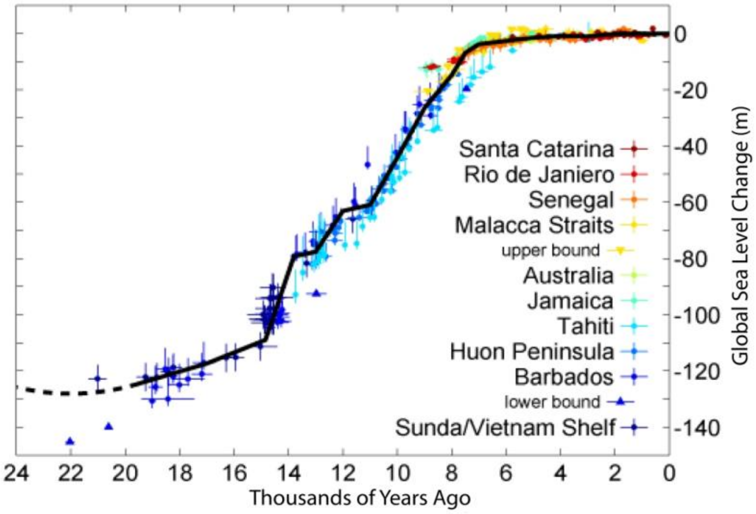

Fig. 2 GSL for the last 24,000 years. During the last 6,000 years, GSL has been exceptionally stable with changes on the order of 0.1 m per century. Human civilizations have not experienced larger rates, which has created a normalcy bias toward the belief that GSL is inherently stable.

Considering the high costs of adaptation and potential disasters caused by coastal hazards, both over and under-protection/adaptation can be very costly and challenging for national economies. Adaptation taking into account a potential rapid LSL rise is economically expensive, culturally difficult to communicate, and legally and politically difficult to implement. Our civilization has a normalcy bias caused by more than 6,000 years of experience with a relatively stable GSL, which created the general concept that sea level does not change significantly through the life time of a human being or even on time scales of several centuries (Figure 2). During the existence of human civilization, typical GSL changes were on the order of 0.1 m per century. It is difficult to communicate that climate change might cause GSL to change much faster than any of the changes human civilizations have experienced. Even on local scale, LSL has been very stable except for a few areas where coastal subsidence or rapid land uplift caused changes discernible withing a typical human lifespan. However, paleo data for the last 800,000 years (Hansen *et al.* 2008) shows that changes on the order of 5 m per century are possible, and changes on the order of 1 to 2 m per century are normal (Plag and Jules-Plag 2013). Due to large spatial variability of LSL, this translated into a PDF for LSL with changes on the order of 3 m per century still having high probabilities, while much larger changes cannot be excluded.

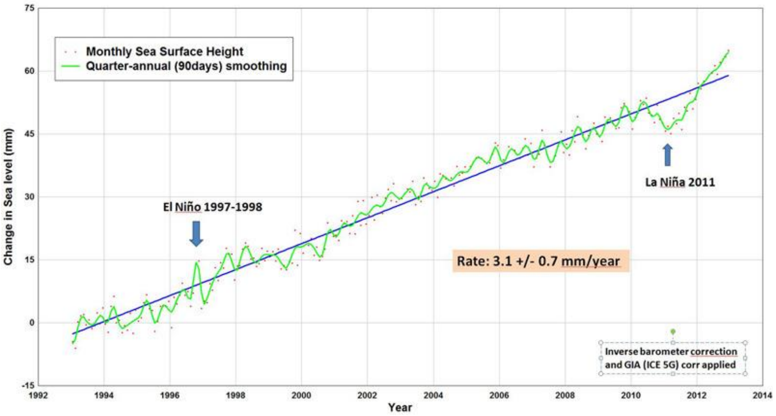

Fig. 3 GSL variations determined from satellite altimetry for the period 1993 to 2013. Note that Fasullo *et al.* (2013) attribute the dip in the GSL curve around 2010.5 to the flooding in Australia after a prolonged drought.

GSL displays interannual to decadal variability on the order of centimeters (Figure 3)[1]. This variability has been related to atmosphere-ocean modes and to changes in land water storage (Fasullo *et al.* 2013). The interannual to decadal variability shows large spatial variability, which can amount to up to 0.20 m over two decades, not accounting for additional contributions from local vertical land motion. Partly, the variability is caused by internal ocean processes and partly by interaction with the water cycle and the atmosphere (Meyssignac and Cazenave 2012). At time scales of 50 years, spatial variability

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[1] From http://www.space.dtu.dk/english/Research/Scientific_data_and_models/Sea-Level-Change; accessed on 2013/10/02.

can be as large as 0.15 m (Plag, 2006; Meyssignac *et al.*, 2012).

2. Need for interannual to decadal LSL projections

In many coastal locations, small changes in mean LSL can significantly change inundation risk and the frequency and magnitude of flooding (Atkinson *et al.* 2013). A rapid LSL rise would amplify risks and the ensuing disasters could challenge our civilization. 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, humans 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 economically and environmentally devastating. 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. Considering the normalcy bias resulting from a very unusual period of stable GSL and the extremely high risk associated with a rapid LSL rise, predictions on decadal time scales are needed to inform timely adaptation and to provide early warning in case there is on onset of rapid changes (Plag *et al.* 2010; Showstack 2013).

Having the ability to reliably predict seasonal to decadal LSL variations would allow for timely detection of the onset of a low-probability, high-impact rapid GSL rise and enable an "early warning system" required to facilitate mitigation and adaptation where and when necessary. Earth observations will be able to identify major ice masses that enter a state of instability, and for these masses, predictive capabilities for their disintegration trajectories need to be developed. Based on such disintegration predictions, LSL could then be forecast with the same time horizon as 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 seasonal to decadal time scales.

Predictive capabilities need to be assessed quantitatively before actionable interannual to decadal predictions can be made available as decision support. No single Earth system model is currently available that can accurately predict past, present, or future LSL changes, and it is unlikely that such a model will become available in the near future. Moreover, some underlying processes (including future greenhouse gas emissions; effects of human "re-engineering" of the planet on climate; response of ice sheets and glaciers to global warming) likely will remain unpredictable on century time scales for a long time to come.

In order to assess our predictive capabilities, it is important to answer three specific science questions: (1) At what time scales does predictability break down for the individual processes contributing to LSL changes? (2) Which of these processes have the potential to cause rapid LSL rise? (3) With what lead time could the onset of a rapid LSL rise be detected, given the limited predictability of several contributing processes?

3. Local sea level equation

The definition of LSL and a cumulative equation for LSL are given in Box 1. LSL as defined there is the quantity directly related to potential impacts of climate change and LSL rise in a given coastal area. GSL is the average of LSL taken over the surface of the oceans. With this definition, changes in GSL equal changes in the Global Ocean Volume (GOV).

Coastal LSL is the result of global, regional and local-scale Earth system processes, which alter sea surface height, land surface height, or both (*e.g.* Plag 2006). These processes include mass relocation in ice sheets, glaciers, land water storage, and oceans; deformation of the solid Earth and gravity field changes caused by the mass relocation; changes in ocean heat storage and ocean currents; changes in atmospheric circulation; tectonic processes; and local coastal subsidence caused by natural and anthropogenic processes. In many locations, detrended LSL exhibits interannual to interdecadal variability exceeding 20 cm, and intraseasonal variability and changes in the seasonal cycle add to LSL variability.

Earth system models available today are not capable of modeling all LSL forcing processes and predicting LSL changes. However, the scientific understanding of the link between individual global, regional and local processes and LSL changes is well developed. Therefore, a local approach can be used to model LSL changes. To accomplish this, we separate LSL into a high-frequency and a low-frequency part and provide cumulative equations for each part, expressing LSL variations as a sum of contributions from the various processes (eqs. (3) and (4) in Box 1).

BOX 1: Cummulative Local Sea Level Equation

We define LSL as the height h of the sea surface above the underlying surface of the solid Earth, i.e.

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

where r_0 and r_1 are the geocentric positions of the sea floor and sea surface, and λ and θ the geographical longitude and latitude, respectively (Plag, 2006). Variations $\xi(t) = h(t) - h_0$ of LSL are the result of variations in r_0 and r_1.

We separate the equation describing LSL into a high-frequency and a low-frequency part:

$$\xi(t) = \xi_{\mathrm{hf}}(t) + \xi_{\mathrm{lf}}(t) \tag{2}$$

with the separation at a period of 2 months (Plag, 2006). For the assessment of impacts, the combined effects of these two parts are important. The high frequency part ξ_{hf} can be written as:

$$\xi_{\mathrm{hf}}(t) = \xi_{\mathrm{waves}}(t) + \xi_{\mathrm{tidal}}(t) + \xi_{\mathrm{atmos}}(t) + \xi_{\mathrm{seiches}}(t) + \xi_{\mathrm{tsunami}}(t), \tag{3}$$

where we have omitted the location dependence. Here we will only consider the low-frequency part ξ_{lf}, which can be written as:

$$\begin{aligned} \xi_{\mathrm{lf}}(\vec{x},t) = {} & S(\vec{x},t) + C(\vec{x},t) + F(\vec{x},t) + A(\vec{x},t) + I(\vec{x},t) + G(\vec{x},t) + T(\vec{x},t) + \\ & P(\vec{x})(t-t_0) + V_0(\vec{x})(t-t_0) + \delta V(\vec{x},t) \end{aligned} \tag{4}$$

where t is time, t_0 an arbitrary time origin, $\vec{x}$ a point on Earth's surface, and ξ is given relative to an arbitrary zero level (Plag, 2006). The processes included in eq. (4) 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.

Equation 4 illustrates the complex nature of low-frequency LSL variations as the result of processes in the global water and energy cycles merged with geodynamic processes and, recently, anthropogenic activities. The processes separate into two large groups, namely those that are mainly volume changes of the ocean water (and thus affect GOV but not Global Ocean Mass (GOM) and those that are associated with significant mass redistribution in the global water cycle (and thus may also affect GOM).

The link between mass redistributions, including mass exchanges between the oceans and other reservoirs in the global water cycle, is given by the mass-LSL equation detailed in Box 2. Eq. (5) has been applied extensively to studies of LSL changes caused by the ice ages and the subsequent Post-Glacial Rebound (PGR, see Mitrovica *et al.* 2010, and the references therein). Main focus has been on the viscous part and the determination of the radial viscosity profile of the Earth mantle. There are still considerable inter-model differences in predictions of present-day PGR signals in LSL, surface displacements, geoid, and rotation (*e.g.*,

BOX 2: Local Sea Level Changes Caused by Mass Redistribution

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. The governing equation that links mass redistribution to LSL variations ξ (first introduced by Farrell & Clark, 1976) can be written as:

$$\xi(\vartheta,\lambda,t) = c(t) + \int_{-\infty}^{t}\int_{0}^{\pi}\int_{0}^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t') \tag{5}$$

$$\frac{\mathrm{d}}{\mathrm{d}t'}\left\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda,t') + \left[1-O(\vartheta',\lambda',t')\right]\rho_{\mathrm{L}}\eta(\vartheta',\lambda,t')\right\}\sin\vartheta'\mathrm{d}\lambda'\mathrm{d}\vartheta'\mathrm{d}t',$$

where ϑ, λ, and t are co-latitude, longitude, and time, respectively, ρ_{W} and ρ_{L} are the densities of the ocean water and the load on land (water or ice), respectively, G is the Green's function for LSL, O the ocean function, defined to be one over ocean and zero over land, and η the accumulated ice load change due to mass added or removed from land. $c(t)$ is determined such that mass is conserved. ξ as defined by eq. (5) is a continuous continuation of LSL onto the continents, and the true LSL has to be defined as $\widehat{\xi} := O\,\xi$. The mass-LSL equation (5) assumes instantaneous distribution of the water in the global ocean and is appropriate at seasonal to longer time scales (see Plag, 2006, and the reference therein). Over the last two decades, eq. (5) has been augmented by several groups (e.g. Milne et al., 1999; Mitrovica & Milne, 2003; Kendall et al., 2005).

Chambers *et al.* 2009), which originate mainly in differences in ice history and the treatment of rotational effects. Using eq. (5) to describe the relation between present-day mass changes and LSL so far has been restricted to a few examples (*e.g.*, Plag and Juettner 2001; Mitrovica *et al.* 2001; Plag 2006; Mitrovica *et al.* 2009; Bamber *et al.* 2009).

Major mass redistribution in the global water cycle can result from significant mass loss from ice sheets, ice caps, and glaciers. Net ice-mass depletion of land-based ice will add to net water mass in the ocean unless it is intercepted by surface water or terrestrial storage reservoirs. The mass loss is accomplished by direct climate forcing (through changes in precipitation, melt rate, *etc.*) and by dynamic changes (*e.g.*, subglacial sliding, iceberg calving) that can be indirectly and non-linearly influenced by climate. Dynamic changes can act to accelerate mass loss from glaciers and ice sheets, but generally not to retard it. If these mass changes are known sufficiently, for example, from model predictions, then the resulting LSL variations can be calculated using eq. (5).

Predictions of GSL from land ice sources depend critically upon numerical simulations and require knowledge of atmospheric and oceanic forcing as well as geometric landscape boundary conditions. While significant progress has been made in ice sheet numerical modeling capacity, robust operational models do not yet exist for prediction (Libscomb *et al.* 2009). Chief among obstacles to be overcome are a lack of knowledge of the processes of subglacial sliding (boundary slip) and iceberg calving. Solutions to these problems and limitations are being sought, and in the meantime, predictions based on climate proxies and approximations of dynamics (*e.g.*, Pfeffer *et al.* 2008) provide temporary "placeholder" solutions.

4. A modular, coupled Earth system model for LSL

Equation 4 can be implemented in a modular, coupled model representing the relevant Earth system processes and ensuring consistency between these processes. Fig. 4 displays the main modules of a modeling framework for LSL changes. Ideally, all individual modules would be at the same level of internal complexity and fully coupled, representing all interactions between the four main modules. Most Atmosphere-Ocean General Circulation Models (AOGCMs) include a reasonably well developed coupled atmosphere and ocean system, but the physical processes for ice sheets, glaciers, sea ice, biosphere, land use changes, and land water storage are not sufficiently represented. Advanced land water storage models such as the Global Land Data Assimilation System (GLDAS) account for hydrological feedbacks in detail and provide high-resolution water storage predictions. Empirical models for ice sheets and glaciers based on recent observations are likely to provide better results than physical models, which have not reached a high degree of predictive capabilities. Similarly, separate sea ice models forced by climate model output might get the best modeling of the sea ice extent. Considering these diverse state-of-the-art-models, it is of advantage to develop the modular model depicted in Fig. 4 as an extendable and scalable framework, in which the individual modules successively can be improved and couplings can be added as they are better understood. By allowing for maximum usage of all available information, with some processes better constrained by observations and models and other processes less constrained, the modular approach provides the basis for assessing in detail the uncertainties, including their spatial variability.

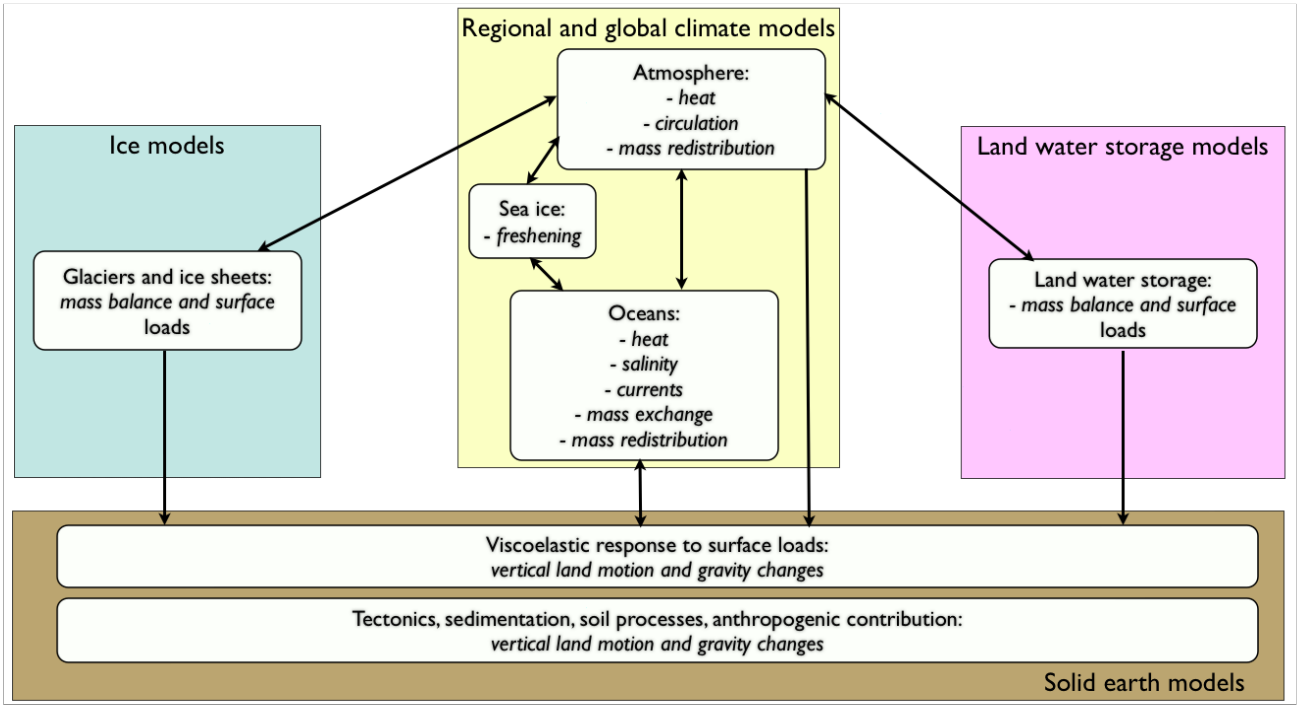

Fig. 4 Structure of the modular LSL modeling framework. The upper three boxes are modules representing the fluid envelope of the solid Earth. Mass exchanges of the ocean with land ice and land water storage represent the main mass fluxes. Heat exchange with the atmosphere contributes to steric changes of the ocean and impacts currents. Mass redistribution in the fluid envelope loads the solid Earth and leads to mass redistribution in the ocean. The arrows represent couplings between the modules including mass fluxes, heat exchange, surface forces, and gravitational forces.

5. Discussion

A scalable modular Earth system modeling framework for LSL changes can be used to study the predictability of LSL on intraseasonal to interdecadal time scales. Continuous observations of key components of the Earth system (*e.g.*, the ice sheets, ice caps and major glaciers, ocean currents, ocean temperature, land water storage, sea surface height changes, vertical land motion) and a combination of global and regional system models that assimilate these observations provide a basis for forecasts of short-term (years) and intermediate (decades) LSL changes. This system modeling framework is currently under implementation. Modules of the system modeling framework will include (1) global models (atmosphere and oceans, ice sheets, glaciers, continental hydrosphere), (2) regional models for steric effects, (3) local models for vertical land motion, and (4) physical models to convert global processes into local effects. The modular system model will provide a framework for data assimilation and model integration. In order to improve predictive capabilities, assimilation of observations on global to regional scales (*e.g.*, gravity field, Earth rotation, sea surface heights) will constrain models, while regional and local observations (*e.g.*, InSAR, GNSS, ground observations) will inform specific processes. The system model ensures global consistency for key Earth system variables, including mass and momentum conservation. The modular nature of the system enables rapid integration of progress made in any of the modules by the project team or by other groups working on relevant models.

The seasonal to decadal LSL variability (see Section1) observed by satellite altimetry for more than two decades and by tide gauges for more than 50 years can be used to assess the predictive capabilities of models for the processes that force these LSL variations. There is considerable uncertainty in the relative contribution of the various processes that cause the spatial variability at interannual to decadal time scales and the extent to which models have predictive capabilities for this variability.

The modules of the system modeling framework will be validated by comparing hindcast predictions of LSL changes with observations from 1950 to present. Special attention will be given to the increasing level of significance of processes, such as ice dynamics, that have become important now but were less active in the past. The validation will be set up such that it supports a full assessment of the predictive capabilities of individual modules as well as the integrated system, and provides quantified uncertainties. This will provide feedback on the predictive capabilities of individual modules, including global to regional climate models.

References

Atkinson, L. P., T. Ezer, and E. Smith, 2013: Sea level rise and flooding risk in Virginia. *Sea Grant Law and Policy Journal*, **5**, 3--14.

Bamber, J. L., R. E. M. Riva, B. L. A.Vermeersen, and A. M. LeBrocq, 2009: Reassessment of the potential sea-level rise from a collapse of the West Antarctic ice sheet. *Science*, **324**, 901-903, doi: 10.1126/science.1169335.

Chambers, D., J. Famiglietti, I. Velicogna, and R. S. Nerem, 2009: The global water cycle 2003-2008: Implications for long-period sea level change. *Geophys. Res. Abstracts*, **11**, EGU2009-10107.

Church, J., T. Aarup, P. Woodworth, W. Wilson, R. Nicholls, R. Rayner, K. Lambeck, G. Mitchum, K. Steffen, A. Cazenave, G. Blewitt, J. Mitrovica, and J. Lowe, 2010: Sea-level rise and variability: Synthesis and outlook for the future. *Understanding Sea-Level Rise and Variability*. J. Church, P. L. Woodworth, T. Aarup, S. Wilson, Eds., Wiley-Blackwell, 402-419.

Edwards, R., 2008: Sea levels: science and society, *Progress in Physical Geography*, **32**, 557--574.

Ezer, T., 2013: Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophys. Res. Lett.*, **40**, 5439–5444, doi:10.1002/2013GL057952.

Ezer, T., L. P. Atkinson, W. B. Corlett, and J. L. Blanco, 2013: Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *J. Geophys. Res. Oceans*, **118**, 685–697, doi:10.1002/jgrc.20091.

Farrell, W. E. and J.A. Clark, 1976: On postglacial sea level. *Geophys. J. R. Astron. Soc.*, **46**, 647--667.

Fasullo, J. T., C. Boening, F. W. Landerer, and R. S. Nerem, 2013: Australia's unique influence on global sea level in 2010–2011. *Geophys. Res. Lett.*, **40**, 4368—4373, doi: 10.1002/grl.50834.

Hallegatte, S., 2012: Economics: The rising costs of hurricanes. *Nature Clim. Change*, **2**, 148—149, doi: 10.1038/nclimate1427.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Clim. Change*, **3**, 802-806, doi: 10.1038/nclimate1979.

Hansen, J., M. Sato, P. Kharecha, D. Beerling, V. Masson-Delmotte, M. M. Pagani, Raymo, D. L. Royer, J. C. Zachos, 2008: Target atmospheric CO2: Where should humanity aim? *The Open Atmospheric Science Journal*, **2**, 217-231.

Horton, B. P., S. Rahmstorf, S. E. Engelhart, and A. C. Kemp, 2014: Expert assessment of sea-level rise by ad 2100 and ad 2300. *Quaternary Science Reviews*, **84**, 1-6, doi: 10.1016/j.quascirev.2013.11.002.

Kendall, R. A., J. X. Mitrovica, and G. A. Milne, 2005: On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. *Geophys. J. Int.*, **161**, 679--706.

Kopp, R. E., 2013: Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophys. Res. Lett.*, **40**, 3981–3985, doi:10.1002/grl.50781.

Lipscomb, W., R. Bindschadler, E. Bueller, D. Holland, J. Johnson, and S. Price, 2009: A community ice sheet model for sea level prediction. *Eos, Trans. Am. Geophys. Union*, **90**, 23.

Little, C. M., N. M.Urban, and M. Oppenheimer, 2013: Probabilistic framework for assessing the ice sheet contribution to sea level change. *Proc. Nat. Academy Sciences USA*, **110**, 3264--3269.

Marcott, S. A., J. D. Shakun, P. U. Clark, and A. C. Mix, 2013: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, **339**, 1198-1201.

Meyssignac, B. and A. Cazenave, 2012: Sea level: A review of present-day and recent-past changes and variability. *J. Geodynamics*, **58**, 96–109.

Meyssignac, B., M. Becker, W. Llovel, and A. Cazenave, 2012: An assessment of two-dimensional past sea level reconstructions over 1950--2009 based on tide gauge data and different input sea level grids. *Surv. Geophys*, doi:10.1007/s10712—011--9171--x.

Milne, G. A., J. X. Mitrovica, and J. L. Davis, 1999: Near-field hydro-isostasy: the implementation of a revised sea-level equation. *Geophys. J. Int.*, **139**, 464--482.

Mitrovica, J. X. and G. A. Milne, 2003: On post-glacial sea level: I. General theory. *Geophys. J. Int.*, **154**, 253--267.

Mitrovica, J. X., N. Gomez, and P. U. Clark, 2009: The sea-level fingerprint of West Antarctic Collapse, *Science*, **323**, 753-756, doi: 10.1126/science.1166510.

Mitrovica, J. X., M. E. Tamisiea, J. L. Davis, and G. A. Milne, 2001: Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, **409**, 1026--1028.

Mitrovica, J. X., M. E. Tamisiea, E. R. Ivins, L. L. A. Vermeersen, G. A. Milne, and K. Lambeck, 2010: Surface mass loading on a dynamic earth: Complexity and contamination in the geodetic analysis of global sea-level trends, *Understanding Sea-Level Rise and Variability*, J. Church, P. L. Woodworth, T. Aarup, and S. Wilson, Eds., Wiley-Blackwell, 285--325.

National Research Council, 2013: Abrupt impacts of climate change: Anticipating surprises. Washington, D.C., The National Academies Press.

Pfeffer, W. T., J. T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, **321**, 1340-1343, doi: 10.1126/science.1159099.

Plag, H.-P., 2006: Recent relative sea level trends: an attempt to quantify the forcing factors. *Phil. Trans. Roy. Soc. London*, **A**, **364**, 1841--1869.

Plag, H.-P., and S. Jules-Plag, 2013: Sea-level rise and coastal ecosystems. *Vulnerability of Ecosystems to Climate*, R. A. Pielke Sr., T. Seastedt, and K. Suding, Eds., vol. **4** of Climate Vulnerability: Understanding and Addressing Threats to Essential Resources, Elsevier, 163-184.

Plag, H.-P. and H.-U. Juettner, 2001: Inversion of global tide gauge data for present-day ice load changes. *Proceedings Second Int. Symp. on Environmental Research in the Arctic and Fifth Ny-Alesund Scientific Seminar 23-25, February 2000, NIPR, Tokyo*, O. Watanabe, and T. Yamanouchi, Eds., Special Issue, No. 54, Memoirs of the National Institute of Polar Research, 301-317.

Plag, H.-P., J. Adegoke, M. Bruno, R. Christian, P. Digiacomo, L. McManus, R. Nicholls, and R. van de Wal, 2010: Observations as decision support for coastal management in response to local sea level changes. *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2)*, Venice, Italy, 21-25 September 2009, J. Hall, D. E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306. doi:10.5270/OceanObs09.cwp.69.

Rowley, R. J., J. C. Kostelnick, D. Braaten, X. Li, and J. Meisel, 2007: Risk of rising sea level to population and land area, *Eos, Trans. Am. Geophys. Union*, **88**, 105, 107.

Sallenger, A. H., K. S. Doran, and P. A. Howd, 2012: Hotspot of accelerated sea-level rise on the Atlantic coast of North America, *Nature Climate Change*, **2**, 884–888, doi:10.1038/nclimate1597.

Showstack, R., 2013: Concern about abrupt climate changes prompts call for early warning system. *EOS, Trans. Am. Geophys. Union*, **94**, 498-499, doi: 10.1002/2013EO510003.

Velicogna, I. and J. Wahr, 2005: Greenland mass balance from GRACE, *Geophys. Res. Lett.*, **32**, L18505, doi:10.1029/2005GL023955.

Velicogna, I. and J. Wahr, 2006: Measurements of time-variable gravity show mass loss in Antarctica. *Science*, **311**, 1754-1756.