**Decadal Survey – Sea Level Change**

**QUESTIONS:**

1. *What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*

***How much will sea level rise (by the end of the 21st century)?***

Space-based and ground-based observations over the last century have shown that sea level is rising on a global scale. A continued rise over the next century and beyond would pose a serious financial and social threat to coastal communities and infrastructures as people and structures may need to be relocated to adapt to flooded coastal zones. By various estimates hundreds of millions of people and hundred of billions of dollars in infrastructure are at risk (Kamal-Chaoui et al, 2009). In addition, a national security threat might exist from the social stresses of potentially large population motions within and across national borders (DoD, 2014). Hence, it is of high importance to increase our ability to predict potential future rates of sea level change under different climate scenarios. Current estimates of Sea Level Rise (SLR) range from *0.3 to 2 m by 2100* (Melillo et al, 2014). This large range makes it difficult for government and business to address the risk appropriately. If the global value is as uncertain as indicated by these vastly different estimates it is impossible to predict regional to local changes along the coasts. However, once global to regional uncertainties are minimized, models of coastal variability (tides, storm surge, elevation models) can be used to bound the percentage change along the coast.

Thus, it is necessary to have a global observing system in place that then not only observes the current rates of global and regional sea level rise but also helps us to improve our understanding of its causes and the physics needed to better model and predict it. Sea level change is a non-linear and highly complex response to changes in global climate and is, thus, not only a concern to the oceanographic community but requires research by the entire water cycle research community including glaciology and hydrology. In particular, the ocean and cryosphere have very long response times to disturbances (many decades to thousands of years).

***Key observables:***

* Sea surface height and ocean mass: global and regional patterns >50 km
* Water mass flux between ocean and land
  + Land hydrology/ocean exchange (5-10 year fluctuations)
  + Ice mass change; ice velocities (10-100+ years)

When considering implementing a future global observation system there are two subquestions to consider that address necessary observables in order to reduce uncertainties in future predictions:

***a) How can we separate short term from long term variability?***

***Key point:*** *Extending the ocean observations of sea level (altimetry) and mass (gravimetry) necessary to distinguish between interannual/decadal variability (10-20 years) and long term trends/acceleration. (50 years or longer).*

***Key measurements:*** *Ocean altimetry; Gravimetry*

Over the past two decades, we have observed a global rate of ~3 mm/yr sea level rise, about 2/3 from ice (glaciers and ice sheets) and 1/3 due to thermal expansion. With two decades of altimetry and one decade of gravimetry observations, combined with a global in-situ ocean temperature and salinity sensing network (CTD, ARGO), we now have a better understanding of the regional patterns of oceanic variability and the heat vs. mass distribution in the ocean. The most important question is how will the contributing processes respond to changes in future climate and what will be their aggregated impact be on sea level change..

Limitations in the fidelity of current state-of-the-art models prevent us from being able to reproduce even the current observed SLR rates in the ocean (e.g. Pacific Decadal Oscillation variability). Thus, while there is still a lack of understanding of some of the most important physical mechanisms that drive variability in the ocean on various time scales it is of high importance to continue to monitor current rates and patterns. Continuing the observing system currently in place to monitor the ocean will be crucial to the ability to separate interannual and decadal variability from a trend or acceleration and to connect the large scale variability to coastal systems.

***b) Are the contributions changing over time?***

***Key points:*** *Monitoring the water mass flux between components (ocean, land, land ice) necessary for improving physical understanding of the drivers. Land ice as the biggest potential contributor needs particular attention*

***Key measurements****: Gravimetry; Altimetry; InSAR; Ice penetrating radar*

As touched upon above, sea level change is essentially a non-linear response of the water cycle to changes in atmospheric conditions. The primary contributors to sea level change are density changes of the ocean and freshwater fluxes. Density changes, global and regional, can mostly be bounded by a combination of space based altimetry and gravimetry and models, which can be addressed with the implementation to answer a). Mass changes (currently directly measured by GRACE) are complex in their origin on various time scales and have the potential to cause the biggest and most rapid change in global sea level. The primary contributions include variability in land hydrology, atmospheric mass transports, and ice mass change. Currently, land hydrology and atmospheric moisture transports have high impacts on interannual time scales, and are important to explaining the current decade-long satellite observations. However, ice mass variations, clearly have the greatest potential for impacting sea level change in the future. The most significant uncertainties in ice sheet model predictions stem from currently insufficiently observed boundary conditions and parameters. Extending the ice observing system to include measurements of velocities and bed topography will help to constrain ice sheet models better to reflect sudden and long term changes in ice flow.

1. *Why are these challenge/questions timely to address now especially with respect to readiness?*

***Key points:*** *Measurements are needed to reduce uncertainties in projections to a level where they are useful to decision makers, however, no observing system is in place after ~2020.*

***Key tasks:*** *Monitoring ocean to track unexpected (unmodeled) changes in contributions and patterns and separate short term from long term change. Reduce uncertainties in ice sheet projections as key player for long term change.*

*Ocean Observing System:*

While space observations have been available to help our understanding of sea level change on a global scale for at least the past two decades, the current program is presently only fully funded through about 2020 (GRACE FO: 2017; Jason-3: 2015/6 launch dates). Tentative plans are in place to fund continuity ocean altimetry through about 2025 (Sentinel 6A&B / Jason-CS: ~2020 and beyond), however, these continuity missions are not yet fully confirmed by NASA/NOAA, and there is no firm approval for a gravimetry continuity mission beyond GRACE FO. There are currently processes on interannual to decadal time scales that cannot be unraveled without having a longer time series of data. In order to distinguish decadal/interannual variability from a trend (i.e. 50 years) a long enough observational record needs to be established covering at least one full cycle (ideally two) - this could be achieved by extending altimetry and gravimetry measurements. It is important to note that the recent NRC Panel on *Continuity of NASA Earth Observations from Space: A Value Framework* ranks altimetry and gravimetry observations very highly in terms of science value provided and cost.

*Land Ice Observing System:*

Another key to improved understanding and prediction is to improve the physics in current ice sheet models that predict sea level change. This requires a continuation of current measurements of ice change plus selected new measurements. Note that we require continuity to help us understand long term ice sheet physics and average parameter values, but also to look for nonlinear rapid changes in ice dynamics (collapses) that are extremely difficult to predict even with excellent models.

For this ice monitoring system and to help assimilate data into and tune ice sheet physical models we require ice mass (GRACE-type), ice elevation (ICESat-2), and ice sheet velocity (NISAR and other InSAR) measurements from space. Note that after the GRACE Follow-On and ICESat-2 launch 2017 with a lifetime goal of 5 years there is currently no plan in place to continue these measurements. The NISAR mission should provide ice velocity data through about 2025 on the current development schedule.

One significant short coming in state-of-the-art ice sheet modeling is the limited knowledge of bed topography. Grounding line retreat is highly depended on the slope the ice is resting on – a downward slope speeds up the flow whereas an upward slope slows the flow down. Currently, ice sheet bed topography is known at mixed scales of resolution and vertical accuracy, generated from gravimetry, and sparse local airborne ice penetrating radar measurement sets. A space-based ice-penetrating radar with enough power to image the bottom of the ice sheets would help substantially improve the knowledge of bed topography, and potentially give some insight into ice layers and hence history as well.

1. *Why are space-based observations fundamental to addressing these challenges/questions?*

***Key points****: In-situ measurements only provide local views. Space observations are needed to increase physical understanding of global processes and connect regional to local changes.*

Space based observations are fundamental to understanding sea level change as they are the only means to provide a global view of the rates of sea level as well as contributing components. In situ observations only provide a local view and are hence, difficult to use to separate different contributions and remote forcing. Only global observations can provide a view of a) global to regional changes in the ocean and b) paint a clear picture of the contributions of the water cycle.

NASA’s multi-decadal experience with ocean altimetry, ocean mass, and ice mass/elevation/velocity measurements in conjunction with assimilating modeling systems have now placed us in position to develop more quantitative analyses for specifying observational requirements aimed at improving projections of sea level rise. This experience base and modelling capability also enables a candidate method for suggesting measurement system priorities relative to having the largest impact on reducing uncertainty in future SLR projections.

As underlined before, the biggest uncertainties stem from our lack of knowledge of the future behavior of the ice sheets. With a total ice mass to raise sea level by more than 60 m, the ice sheets also have the biggest potential to impact global sea level significantly. While the ice sheets are geographically limited it is still impossible to comprehensively monitor changes or static properties such as bed topography using in-situ or airborne observations only. Particularly, the interior of the ice sheets remains almost inaccessible when limited to ground based or airborne observations.

***Because of the risk to society, because of NASA’s clear leadership in measuring and understanding sea level rise in the last two decades, and because of the variety of space borne missions needed for a complete picture of the forcings and responses, we believe that a Panel under this NRC Committee should be devoted to Sea Level.***

References:

Kamal-Chaoui, Lamia and Robert, Alexis (eds.) (2009), “Competitive Cities and Climate Change”, OECD Regional Development Working Papers N° 2, 2009, OECD publishing, © OECD

U.S. Department of Defense, “2014 Climate Change Adaptation Roadmap”, <http://www.acq.osd.mil/ie/download/CCARprint_wForeword_c.pdf>

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2