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Introduction

Sea level change (SLC) is a fundamental and sensitive indicator of multiple changes in the Earth system occurring as a consequence of the rise in Earth's heat uptake mostly caused by increasing concentrations of greenhouse gases. Sea level changes due to the melting of ice sheets and glaciers, thermal expansion of the oceans as a result of increases in heat content, changes in land water storage, changes in ocean circulation, gravitational self-attraction and loading, GIA and a variety of other factors. As such, sea level science is an inherently multi-disciplinary endeavor. Glaciologists, oceanographers, hydrologists, geodesists, solid-Earth geophysicists, atmospheric and climate scientists, and a broad spectrum of other disciplines, are involved in understanding how changes in the coupled Earth system contribute to SLC along coastlines. According to the 2014 U.S. National Climate Assessment, global average sea level will rise between 6 and 33 cm in the next 20 years. The socioeconomic importance of coastal infrastructure and population centers threatened by SLC cannot be overstated; over a hundred million people live in densely-populated regions within 1 m of present day mean sea level and even a rise of 20 cm will have profound impacts on these communities as flood risks and return frequencies of extreme events increase. It is vital to continuously monitor sea level and the processes that contribute to its change to gain insight into how these processes are changing and to predict the magnitude and timescales of future SLC. Current research focuses on understanding the observational record of ice mass loss, SLC, changes in ocean heat content, and other variables, so that we can build better dynamic and empirical models to predict future change, especially its regional variations.

Science and Societal Benefits

The scientific and societal benefits of interdisciplinary sea level research are numerous. SLC is one of the fundamental barometers of how the Earth is responding to climate change, especially when averaged globally. The extra energy from climate change is reflected primarily in the melting of ice and the thermal expansion of ocean waters, though sea level can also be affected by changes in land water storage due to modes of climate variability (e.g., ENSO, PDO, NAO, etc.) and anthropogenic effects (e.g., pumping of water from aquifers, construction of artificial reservoirs, oil and gas extraction). Measurements of SLC and its components are the primary data records used for evaluating and benchmarking climate models and their projections. However, there is also an enormous societal benefit from SLC science. Future sea level rise will have a profound impact on coastal infrastructure and societies. Improving the accuracy of current regional sea level monitoring and future predictions is critical to coastal stakeholders as they plan their responses to sea level rise. Only with this information can these stakeholders make rational decisions about the construction of new facilities and coastal protection infrastructure or if certain coastal areas need to be abandoned altogether.

The Role of Satellite and Airborne Observations

Satellite and airborne observations are crucial for understanding SLC and its components because of the global and regional comprehensive coverage they provide. This coverage allows global or regional averaging of the data, which reduces the variability observed in point measurements, allowing trends to be more easily identified. Satellite radar altimeter measurements, when averaged globally, can observe global mean sea level variations that on decadal and longer timescales are largely driven by climate change. Satellite gravity measurements provide a similar advantage in that complex mass redistributions on the Earth's surface are naturally integrated by the satellite orbit into unambiguous changes in the regional distribution of ice and water mass. Satellite gravity measurements, together with laser altimetry, airborne radar sounding measurements of ice thickness, and InSAR measurements of ice motion, have become crucial tools for understanding how ice sheets and glaciers are responding to climate change. Satellite gravity measurements also provide a way of monitoring natural and anthropogenic changes in land water storage, which dominate global mean sea level variations on annual and interannual time scales. Tracking the difference between altimeter sea level measurements and satellite gravity measurements of ocean mass changes offers a method of greatly enhancing the measurements of changes in ocean heat content that are monitored using the Argo network of profiling floats above 2000 m depth, but not below. Another important parameter is vertical crustal motion, which impacts relative SLC along the coasts and our interpretation of the tide gauge record. These motions are also critical in that they guide the interpretation of geodetic measurements related to SLC (e.g., GRACE, ICESat, GNSS, etc.), such as due to GIA.

To date, the primary satellite tools for monitoring sea level-related parameters are: (i) satellite radar altimetry (for measuring sea surface height - e.g. TOPEX/Poseidon, Jason-1, Jason-2, and soon Jason-3 and soon Jason-CS/Sentinel-6 and SWOT); (ii) satellite gravity (for measuring ice mass loss and mass contributions to SLC - e.g. GRACE and soon GRACE Follow-On; (iii) satellite radar and laser altimetry (for estimating the changing volume/mass of ice sheets and glaciers- e.g. ERS/Envisat/CryoSat-2, ICESat and soon ICESat-2); (iv) satellite-based InSAR (for measuring the speed of outlet glaciers – ERS, Envisat, RADARSAT-1/2, ALOS PALSAR-1/2, and soon NISAR); (v) radar echo sounding from airborne platforms for measuring the thickness of glaciers and ice sheets (Operation IceBridge) and (vi) GNSS (Global Navigation Satellite Systems, e.g. GPS for measuring vertical crustal motion). Almost all of these measurements depend on a precise terrestrial reference frame provided by geodetic measurements (e.g., SLR, VLBI, GNSS and DORIS). Together, these observations have given us an unprecedented understanding of SLC over the last several decades. Since 1992, global average sea level has risen at a rate of 3.3 ± 0.4 mm/year and ~60% of this is due to ice mass losses from Greenland, Antarctica, mountain glaciers, and changes in land water storage.

There are a number of ground and aircraft-based measurements that need to be linked to the satellite measurements. This is mainly accomplished through GNSS positioning (of tide gauges, altimeters on aircraft and UAVs, the solid Earth, etc.) using a precise terrestrial reference frame (TRF) that ties all the measurements together. These GNSS measurements are being used both to supplement the satellite data (e.g. InSAR measurements of crustal motion and glacier velocities) and also for validation purposes (e.g. tide gauge measurements of sea level compared to satellite altimetry). Other measurements have been producing stand-alone products from airborne surveys that have targeted regions of Greenland, Antarctica, Alaska, Patagonia and the Canadian Arctic where ice loss is especially dramatic at rapidly evolving outlet glaciers. Especially important results have been derived from NASA's Operation IceBridge. The Argo network of profiling ocean floats has been critical for assessing changes in upper-to-mid ocean heat content and the resulting thermal expansion contributions to SLC.

Future Observations Needed to Advance the Science

Although we have been able to quantify and partition the last two decades of SLC, this has only marginally translated into better numerical models that can project future ice mass loss and SLC with an accuracy that is useful for stakeholders. A key challenge in sea level science is developing a better understanding of the dynamics of the glaciers and ice sheets, including their interactions with the atmosphere, a warming ocean, and their breaking up into icebergs along calving walls, so that we can predict how quickly they will disintegrate and contribute to SLC. This remains a leading source of uncertainty for projecting sea level rise over the next 20-200 years. Other problems being studied by sea level scientists include understanding regional variations in SLC and how to project them; obtaining better estimates of vertical crustal motion to understand how it exacerbates SLC in some locations and how it can help us better understand ice mass loss.

The main missing piece of the current suite of space-based observational assets used for sea level science is the lack of a dedicated InSAR mission to provide continuous and systematic estimates of glacier velocities, changes in grounding line position and crustal motions immediately adjacent to regions of large ice mass change. However, there are also numerous improvements to the existing observational tools that would greatly benefit sea level science including: a) improved spatial and temporal resolution of satellite gravity measurements, b) improvements to the Terrestrial Reference Frame (TRF), c) improved sea level and vertical crustal motion measurements in the coastal zone and improved spatial resolution in the open ocean, and d) high-resolution ocean vector winds from scatterometers. In addition, higher resolution coastal digital elevation models (DEMs) would greatly improve estimates of the impacts of future SLC. Importantly, long (>20 years) time series and measurement continuity is key to a better understanding of sea level change. Continuation of precision satellite altimetry (oceans and ice), radar interferometry, and satellite gravity observations so we can understand the interplay between interannual, decadal, and long-term climate variability is critical for future scientific advances in sea level science. An important missing piece for ocean heat content changes is the role of the deep ocean, which should be addressed by a "Deep Argo" expansion of the Argo network, and include deployment of Argo floats in hard-to-reach places, e.g. in the polar regions often occluded with sea ice cover.

Projections of sea level contributions from ice sheets and glaciers will remain uncertain unless confidence in the atmospheric and oceanic forcing used as input for ice sheet models can be established, and the models are run in a coupled mode, at a high spatial resolution (typically 1 km). Ice-ocean interactions are difficult to address with satellite measurements and require underwater robotic exploration of the ocean-ice interface, the deployment of airborne drop sondes, and multibeam echo sounding of the sea floor as done by NASA's Ocean Melting Greenland (OMG) mission. Significant progress has been made to reconstruct surface mass balance using regional atmospheric climate models constrained by re-analysis data, but more snow radar measurements are needed from airborne platforms to retrieve past accumulation over a larger area. The largest energy source for melting of ice is solar absorption, the modeling of which requires improved understanding of ice albedo that will only come with enhanced observations from satellite radiometers. Novel instruments are needed that can directly measure surface melt volume and snow/firn density. There is also a critical need for more comprehensive coverage of ice thickness over ice sheet, ice shelves and glaciers, which requires radar sounders operating over a variety of frequencies Finally, improved understanding of iceberg calving requires satellites operating at visible and radar wavelengths with a frequent (daily to sub-daily) repeat cycle, combining with in-situ observations using GPS, portable InSARs, and robotic topographic mappers.

Acronyms

Argo	Global array of more than 3000 profiling ocean floats
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ENSO	El Nino Southern Oscillation
GIA	Global Isostatic Adjustment
GNSS	Global Navigation Satellite Systems
GRACE	NASA/DLR mission to measure changes in Earth gravity field (2002-present)
InSAR	Interferometric Synthetic Aperture Radar
NAO	North Atlantic Oscillation
NISAR	NASA ISRO SAR mission
PDO	Pacific Decadal Oscillation
SLC	Sea Level Change
SLR	Satellite Laser Ranging
SWOT	US/France Surface Water Ocean Topography mission.
TRF	Terrestrial Reference Frame
UAV	Unmanned Aerial Vehicle
VLBI	Very Long Baseline Interferometry