Understanding Sea Level Changes

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Abstract--**Sea level change occurs on all timescales, depending on the type of change in question. It also occurs with a continuous range of spatial scales--local, regional, and global. To understand and be able to eventually predict sea level changes is a truly interdisciplinary endeavor. It requires geodetic and non-geodetic measurements of various types from space as well as in situ, while various numerical models for a number of meteorological and geophysical processes or properties are essential or relevant.**

I. INTRODUCTION

Today more than 100 million people worldwide live on coastlines within one meter of mean sea level; any short-term or long-term sea level change relative to vertical ground motion is of great societal and economic concern [1]. The very existence of many island states and deltaic coasts is threatened by sea level rise. As paleo-environment and historical data have clearly indicated the existence and prevalence of such changes in the past [2], new scientific information regarding to the nature and causes and a prediction capability are of utmost importance for the future.

Globally the sea level is estimated to rise at 1.5-2 mm/year for the last century [3] and somewhat faster in the recent decade [4]. But otherwise very little is certain as to the contributions of various meteorological and geophysical causes as a function of space and time. Sea level change occurs on all timescales from seconds to secular, and with a continuous range of spatial scales--from local (e.g., storm surge, land subsidence), to regional (e.g., ENSO, post-glacial rebound), to global (eustatic). While measuring absolute as well as relative (to ground) sea level changes is a geodetic endeavor, to understand and be able to predict sea level changes requires comprehensive, interdisciplinary research in terms of incorporating ancillary data types and various meteorological and geophysical models.

II. CAUSES OF SEA LEVAL CHANGE

There are basically four ways the sea level undergoes changes:

(i) Volume change, as a response to the thermal content and salinity-density compensation of sea water. Also known as the steric effect, it mostly results from atmosphere-ocean thermal interactions, and includes major processes of ENSO, NAO and other meteorological oscillations, and is influenced by deep thermohaline circulations.

(ii) Mass change, due to a number of geophysical and hydrological processes that lead to water exchanges in the Earth-atmosphere-hydrosphere-cryosphere system. These include water exchange from polar ice sheets and mountain glaciers to the ocean, atmospheric water vapor and land hydrological variations such as soil moisture and snow cover, and anthropogenic effects such as water impoundment in artificial reservoirs and extraction of groundwater.

(iii) "Container" change, as a result of solid Earth vertical deformations due to tectonics, rebound of the mantle from past and present deglaciation, and other local ground motions. These affect the relative sea level.

(iv) Dynamic changes, due to external forcings exerted on sea surface. These include waves (capillary, gravity, planetary, tsunami), tides, wind-driven circulations (with dynamic height), pressure-driven topography (via dynamic inverted-barometer effect), density-driven (thermohaline) currents, and geoid-induced sea level changes.

Our current knowledge about the contributions of the various causes for the sea level change is very limited. The very share of the steric versus mass-budget contributions is under debate [5], let alone its spatial and temporal dependence. We are presently not certain whether Greenland and Antarctica are gaining or losing net ice mass [6]. Estimates of mountain glacier melting are quite incomplete [7]; those for global land hydrological budget are far from reliable. Even the amount of artificial reservoir water impoundment is uncertain by perhaps a factor of 2 [8].

III. MEASUREMENTS

Globally the sea level is estimated to rise at 1.5-2 mm/year for the last century and somewhat faster in the recent decade. This conclusion is reached by examining historical tide gauge data [3] and modern ocean altimetry data [4]. In addition, a number of space geodetic measurement types as well as synergistic in-situ and remote-sensing data sources are becoming available. They can be summarized below.

Direct -- geodetic measurements:

(i) Radar altimetry: As this "work horse" measurement of sea surface height is becoming operational (TOPEX/Poseidon, Jason, ENVISat, NPOESS, etc.), improvements in spatial and temporal resolutions of the measurement are highly desirable. Constellation and new technology (e.g., wide-swath) can help greatly.

(ii) Laser altimetry: Air-borne and experimental space-based (e.g., SLA) measurements have been conducted. This new data type would complement (1) especially in altimetric mapping of coastal sea/land areas and inland water bodies, and monitoring the ice sheets (e.g. ICESat).

(iii) Time-variable gravity: Space-based measurement is beginning to yield high spatial resolution data (e.g., GRACE), which, in conjunction with altimetry, are effective in separating steric and mass contributions in the sea level change.

(iv) SAR/InSAR: A powerful new data type useful in monitoring glacial and ice sheet variations.

(v) GPS buoys: They are presently used as calibration/validation tools for altimetry, but potentially useful for independent sea level measurement.

(vi) GPS bistatic reflection: Already demonstrated for proof of concept, this is potentially a new altimetric data type.

(vii) Tide gauges/GPS: Tide gauges represent a long history of relative sea level measurement along the coastline and at island locations. With additional co-located GPS receivers, ground vertical motion and true sea level change can be separated.

Ancillary -- non-geodetic data sources:

(i) Sea surface temperature: Effective space-based measurement giving definitive evidences for thermosteric effect as a function of space and time.

(ii) XBTs: In situ "spot snapshots" of vertical temperature profiles in the ocean, providing direct measurement for thermosteric effect.

(iii) Mixed-layer depth: Possibly measurable from space-based lidar technology, providing global and continuous coverage of thermosteric effect.

(iv) Ocean surface salinity: Possibly measurable from space-based lidar technology, providing global and continuous information about surface salinity component of the steric effect.

(v) Various land hydrology remote sensing, such as soil moisture, snow depth, extent of land water bodies, river runoff, etc.

IV. MODELING REQUIREMENTS

For the same reasons that call for various measurement types, to understand and be able to predict the sea level change requires a host of numerical models. Assuming the availability and continued refinement of meteorological models for the atmosphere-ocean-hydrology general circulation, polar meteorology, as well as coastal dynamics, one needs the following models that deals with the various geophysical processes involved in sea level changes:

(i) Ice dynamics: If the present global warming trend continues, a most immediate and potentially dominant mass-budget contribution to sea level change is likely to come from the melting of ice masses. The melting of temperate glaciers could raise sea level by a few tens of centimeters; the melting of the ice sheets in West Antarctica could raise sea level by several meters [9].

(ii) Glacial isostatic adjustment: Various models currently exist, based on present knowledge (and/or assumptions) about the solid Earth's rheology and the ice history of the last ice age [10]. They differ significantly, and hence is a source of uncertainty particularly in the modeling of relative sea level changes.

(iii) Loading effects: Mass loading effect [11] occurs whenever there is redistribution of surface mass, in the atmosphere, the oceans, and associated with ocean tide and land hydrology. In general, modeling of both elastic and viscous loading effects is necessary. The former is fairly well understood at least on large spatial scales; the latter depends on present knowledge (and/or assumptions) about the solid Earth's rheology, similar to (ii).

(iv) Tides: Solid tides are fairly well modeled as in the elastic loading effect. Ocean tide models have been

greatly improved owing to the TOPEX/Poseidon observations, but continued improvements are necessary [11].
(v) Global gravity field: The geiod defines the static sea surface topography, and departures from the geiod gives the dynamic height. High spatial resolution gravity field model is essential. A state-of-the-art model is EGM96 [12]; new satellite missions of CHAMP, GRACE. GOCE, and future follow-ons will contribute greatly to gravity modeling.
(vi) Maintenance and improvement of the Terrestrial Reference Frame [11] precise to mm level, which is essential for all space-geodetic measurements to bear on sea level measurement.

V. EPILOG

Quantitative assessment of sea level change is important for scientific research on climatic changes as well as immediate societal benefits. While measuring absolute as well as relative (to ground) sea level changes is a geodetic endeavor, further advances in geodetic techniques should measure the sea level changes and consequences in a routine fashion, with enhanced accuracy, geographical coverage, and spatial and temporal resolutions. Research is also being done in exploiting synergistic use of relevant and ancillary measurement types--sea and ice surface height changes, time-variable gravity, solid Earth surface deformations (especially along coastline), all under a uniform terrestrial reference frame, together with in situ measurements from tide gauges, buoys and XBTs, remote sensing data such as sea surface temperature and salinity. These data analyses and interpretation are to be made in the framework of numerical models for various geophysical and meteorological processes that are involved in changing the sea level. A complete knowledge of sea level change can then emerge and used for predictions, not just for the (slow) sea level rise, but indeed for sea level changes "anywhere, anytime".

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