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WCRP White Paper: Sea-Level Rise and Regional Impacts

Based on WCRP Regional Sea Level Rise Workshop report (Detlef Stammer, Jonathan Gregory, WCRP, 2011)
with additional text by Konrad Steffen

Recent projections of global sea-level rise by 2100 C.E. range from 20 cm (*Meehl et al., 2007*) to as much as 2 m (*Vermeer and Rahmsdorf, 2009; Pfeffer et al., 2008*), and sea level is projected to rise in the coming centuries even further. Without adaptation, a rise by 0.5 m would displace 3.8 million people in the most fertile part of the Nile River Delta (*FitzGerald et al., 2008*). A rise by 2 m could displace 187 million people globally (*Nicholls et al., 2011*).

Satellite altimetry data indicate that since 1993, globally averaged sea level has been rising at a rate of more than 2.5 mm yr^{-1} (*Cazenave et al., 2009*). While a lot of effort has been dedicated to the analysis, monitoring and modeling of global sea level trends, a new relevant issue is emerging concerning the regional aspects of the sea level rise (*Slangen et al., 2011*). For impact assessments, information of the impact on the regional scale is often most relevant. Therefore, sea level variations and change should be evaluated locally in addition to the global changes. This requires a good understanding of the various processes involved; hence understanding the various processes contributing to sea level change at a location is a very challenging task because of various temporal and spatial scales involved.

Accurate predictions of regional sea level change on decadal to centennial time scales are therefore required for impact, adaptation and vulnerability assessments, especially for the coastal communities and ecosystems. Observations are key to our understanding of sea-level changes in the past and present, but models are essential to obtain best projections of change in the future. Majority of existing climate models largely disagree about patterns and magnitudes of sea level variability and change on regional scales, and it is entirely unclear whether they have sufficient skill in projecting regional sea level. Understanding these changes in terms of underlying physical and dynamical processes is essential for providing science-based information about the regional sea level change. WCRP convened a workshop in 2011 to; 1) discuss scientific challenges and opportunities in regional and global sea level change observations, research and modeling its relation; 2) identify underlying processes contributing to changes, and their representations in climate models.

Recent research results indicate most of the observed regional changes are steric in nature, to a large degree being caused by redistribution of temperature and salinity in response to changing winds. This advancement in our understanding is due to comprehensive data coverage and correction of observational errors in temperature and salinity changes. However, some local effects (e.g., shelf dynamics, tectonics) may complicate or obscure the relationship between coastal and offshore sea level change. Improvement in knowledge of variability and trends on multi-decadal timescales depends on continuing improvements to observations and analysis from tide-gauge and proxy sources. The newly available data sets allow partitioning of the contributions of the steric changes in thermosteric and halosteric sea levels, revealing that salt changes do matter for regional sea level changes – this type of information was lacking in the past in most parts of the world. Recent research results also suggests that changing winds and associated changes in the flow field and transports are a very important cause for observed changes in regional (steric) sea level changes. This mechanism might also be one of the important drivers for regional sea level changes on decadal and longer time scales.

For example, interannual variability in northeast Atlantic sea level records exhibits a clear relationship to the air pressure and wind changes associated with the NAO, with the magnitude and sign of the response depending primarily upon latitude (*Andersson, 2002; Wakelin et al., 2003*). In the Russian Arctic Ocean, sea level time series for recent decades also have pronounced decadal variability that correlates with the NAO index. In this region, wind stress and atmospheric pressure loading contribute nearly half of the observed sea level rise of 1.85 mm yr^{-1} (*Proshutinsky et al., 2004*).

Other changes such as changes in the Atlantic meridional overturning and gyre circulations are also regionally important, but changes in surface fluxes of heat and freshwater into the ocean will become more important with increasing time scales. To be more complete and quantitative there is need for an extended data base including deep ocean temperature, salinity and pressure information. Such observations are required to determine; (i) where bottom pressure changes are important to sea level variability and change, as a function of time; and (ii) where regions of heat and freshwater uptake (through surface fluxes) are located, which cannot be determined from the current datasets. While it is obvious that wind stress impacts regional sea level on all time scales (decadal to longer time scales), it is not obvious why the wind has been changing during the recent past decades.

As local (relative) sea level rise is among the major threats of future global warming, it is both of primary importance and urgency to develop multidisciplinary studies to understand and discriminate causes of current sea level changes in some key coastal regions, integrating the various factors that are important at local scales (climate component, oceanographic processes, sediment supply, ground subsidence, anthropogenic forcing, etc.). Further, implementation of additional in situ observing systems in vulnerable coastal areas in needed, in particular, tide gauges co-located with GNSS stations for measuring (mainly vertical) ground motions. Improving current altimetry-based sea level observations in coastal zones is critical, and the continuation to develop SWOT (Surface Water and Ocean Topography) satellite mission, a wide-swath altimeter, for accurate future monitoring of local sea level changes at the land-sea interface.

Climate model simulations of future regional sea-level changes due to anthropogenic climate change on multi-decadal timescales likewise show geographical variability, which is substantial compared with the global-mean sea-level rise. The pattern of such future projections can mostly be explained by local temperature and salinity changes, i.e., they are steric in nature, but are likely to be caused by a combination of changes in surface heat and freshwater forcing, changes in redistribution by interior mixing, and trends in the wind-driven and thermohaline circulation. In addition to forced and natural dynamical variability and trends, patterns of regional sea level changes affected by the influence of the geoid and the redistribution of ocean mass, and changes in ice and water mass on land. First syntheses of contributions to regional sea level changes are now available providing information about regional long-term (secular) trends in sea level on a global basis. Corresponding information is available based on climate models, but also from statistical up-scaling approaches. The consistency or inconsistency between these different sources of information has to be tested and discussed. Moreover, similar information is required for decadal time scales.

The following research, observations and modeling imperatives were identified for WCRP in the next decade.
In the following we give a more detailed account of the open issues;

1. *Uncertainties in solid-Earth and gravity models used for predictions/projections.* Such models are required during many stages of analyzing sea level variability and changes. Yet uncertainties remain in existing models, which need to be improved for quantitative regional sea level predictions. With respect to the more immediate elastic deformation, the largest uncertainty resides in the distribution of mass loss that goes into the predictions.

2. Estimates of relative contribution of climate modes to sea level variability. While consensus exists that a major fraction of the observed sea level changes during the last decade are caused by internal climate variability, it is not known what the relative contribution of specific climate modes (ENSO, PDO, NAO, …) is to sea level variability.

3. Intercomparison of climate modes in climate models and observations (amplitudes, periods, phases, internal structures). It is not obvious how realistically climate modes are being simulated by climate models. This calls for a comparison of climate modes in observations and climate models.

4. Change of climate modes as function of CO_2 forcing. We have indications that climate modes will change in a warming climate. Given the clear role of climate modes for regional sea level, it is important to know how climate modes will change in the future.

5. Separation of climate modes and long-term trends (in observations and in models). Regional sea level observed during the last 1-2 decades is strongly influenced by climate modes. It is important to better understand how to separate long-term trends from natural climate variability in observations and models.

6. *Encourage further analysis of proxy and tide gauge data.* For that purpose it is encouraged to make more use of paleo-data to expand the observational data base backward and thereby obtain an enhanced data base to understand long-term trends.

7. We need to understand the degree of decadal variability in sea surface height observations and in forecasts. Similar to long-term trends we also need to better understand and quantify the amount of decadal internal variability in existing observations and in forecasts and projections. Even projections of regional sea level changes over 100 years will be influenced by internal decadal variability.

8. We need to allow for deep ocean-only sampling from GRACE thereby omitting the shallow water mass contributions to large-scale bottom pressure variations. To separate out contributions of mass changes on the shallow shelf from regional sea level variability observed over the deep ocean it is recommended to produce GRACE fields that omit data from shallow areas in the processing of bottom pressure fields.

9. Investigation of contributions of wind forcing changes relative to other forcing components on regional sea level variability and secular changes. While it is obvious that changes in wind forcing are a primary driver for sea level changes observed during the last decades, it is not obvious what the relative contribution of changes in wind forcing and buoyancy forcing is in long-term climate projections.

10. Impact of changes in the wave field on sea level need to be investigated. The wave field impacts the observations of sea level. Moreover, the underlying electromagnetic-bias correction in altimetry has a large uncertainty. It should be investigated how a changing wave field might impact the observations of regional sea level patterns.

11. *Encourage deep ocean observations; better data sets are fundamental*. It is recommended to enhance our data base of deep hydrographic observations (below 2000m depth).

12. Inconsistency in atmospheric forcing – needs to be looked at more critically. The workshop participants acknowledge large remaining uncertainties in surface forcing fields. It is recommended to use ocean (sea level) information to decipher those uncertainties by comparing resulting sea level changes against observations and thereby learn more about the accuracy of the forcing, a strategy that is being pursued in ocean syntheses efforts.

13. *Encourage investigation of whether sea level changes can be attributed to particular radiative forcings and the use of such relationships to constrain projections*. It is encouraged to further quantify the relationship between patterns of observed sea level trends and changes in the various radiative forcings, and use these relationships to better constrain projections of sea level trends in climate models.

14. *Improve studies of fingerprinting ice melting, also by using paleo-data*. Melting polar ice sheets produce a clear pattern in regional sea level. It is encouraged to further investigate those patterns and use them to identify potential contributions of ongoing ice sheet melting in existing sea level observations by also using paleo-data (e.g., salt marshes).

15. *Encourage intercomparison of climate modes in CMIP5 Models and comparison with observations in order to understand model deficiencies and uncertainties, especially structural uncertainty*. Upcoming CMIP5 results need to be compared against observations in terms of climate modes and variability to better understand the role of model deficiencies and uncertainties in simulating corresponding regional sea level variability and change. Respective results are required as input to the AR5 report.

16. *Encourage use of CMIP5 predictions for regional studies of sea surface height on interannual to decadal time scale*. Upcoming CMIP5 projections need to be evaluated with respect to regional sea level variability on interannual and decadal time scales and longer-term trends in regional sea level patterns. Relevant results should be made available as input to the AR5 report.

17. *Encourage further investigations of static responses and impact on ice sheet dynamics*. Sea level will decline in the vicinity of melting polar ice sheets as a static adjustment to an underlying mass redistribution in the Earth system. We need to further investigate the static response and its impact on ice sheet dynamics.

18. *Improve understanding of dynamical response of sea level to climate forcing, including high latitude freshwater forcing*. Enhanced freshwater input will lead to a dynamical adjustment of the ocean. We need to better understand the dynamical response of sea level to polar ice sheet melting and analyze this adjustment in coupled climate models. Remaining modeling and data issues that need attention can be summarized as follows.

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