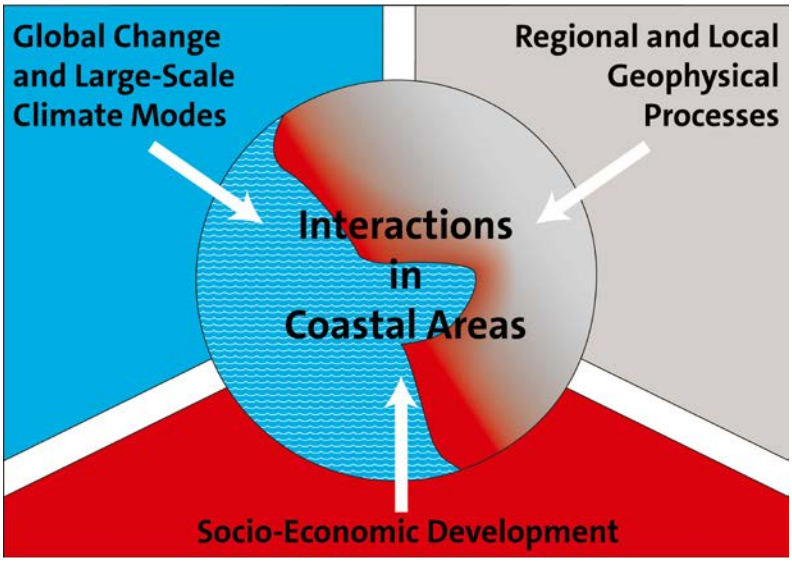
Proposal for establishing a DFG Priority Program (SPP)

SeaLevel: Regional Sea Level Change and Society



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1 Summary

Understanding regional sea level change and its impacts on societies requires new forms of integrated research between natural and social scientists from a wide range of disciplines. To this end a Priority Program (SPP) 'Regional Sea Level Change and Society (SeaLevel)' is proposed to advance the understanding of regional climate-related coastal sea level change and its interactions with socio-economic developments. Work will focus on two study regions, notably the North and Baltic Seas with potential impacts on Germany and the South-East Asia region encompassing several coastal mega cities and delta regions. The selected regions contrast developed and developing countries and thus differ fundamentally in their regional societal impact of and adaptation potential to sea level change. Developing successful strategies to cope with sea level change in these two regions largely depends on advancing our understanding of processes influencing regional sea level, on available scientific information on sea level change at the coastlines and their uncertainty, on available resources and economic power, and on adequate planning and effective local governance structures.

SeaLevel will develop an understanding of the society's response to sea level change in the two study regions by (1) improve the physical knowledge base of regional climate related sea level change, (2) improve projections of sea level change on a regional-to-local scale, (3) investigate which socio-institutional factors enable or hinder coastal societies to cope with changing sea levels, (4) determine the natural and social coastal systems responses to future sea level change, and (5) assess strategies to adapt to sea level change under given technical, economic, cultural, social and political constraints. All of these steps will be performed iteratively and interactively to assure that progress on the climate and geophysical aspects of sea level will be directed toward answering questions about socio-economic impact of and adaptations to sea level rise in our study regions. Through the insight gained, the SPP will create an invaluable knowledge basis for subsequent awareness to sea level rise in coastal zone management efforts of many other endangered places around the globe.

SeaLevel integrates natural science disciplines, which are concerned with the mechanisms of sea level change (physical oceanography, solid earth physics and hydrology), its observation and monitoring (physical oceanography, paleoceanography, geodesy, marine geology, and coastal engineering), as well as social sciences disciplines, which address socio-economic impact of sea level change, coastal human-environment interactions and risk governance (geography, sociology, economics, political science, international law, environmental risk management and communication). Only a fully integrated program, jointly involving natural and social scientists as well as climate and coastal research communities, can provide the scientific basis for development and assessment of adaptation strategies to cope with coastal sea level change.

The study is very timely because of the urgency of the problem and because of many recent disciplinary scientific advances: (1) climate models have reached the quality required to conduct meaningful numerical experimentation at regional-to-local scale, (2) observations have become available for a detailed understanding of processes on a regional-to-local scale (including feedbacks between the ocean, atmosphere, cryosphere, terrestrial hydrology and solid earth), (3) new decision-analytical adaptation pathways have been developed that combine uncertainties inherent in sea-level rise projections and relevant policy processes into a single framework and (4) new approaches for understanding how governance arrangements can be aligned with human-environment interactions, which is particularly relevant for complex coastal systems threatened by see-level rise.

Coastal impacts of regional to local sea level change has been identified by the World Climate Research Program (WCRP) as a high profile research theme. The proposed research can contribute to and benefit from this international effort. Regional-to-local sea level change became an challenging issue in the Fifth Assessment Report of the IPCC, in particular because the lack of sufficient process and regional understanding that hindered a satisfactory assessment. Coastal vulnerability is also one of the priority themes of the Belmont Forum collaborative funding initiative. In its economic assessment of adaptation to climate change, the World Bank has identified sea level rise as the potentially most costly aspect of climate change (World Bank, 2010).

The German research community is very well equipped and ready to tackle this exciting research and has proven expertise in all relevant natural and social science disciplines, bringing together knowledge of ocean and climate observation, ocean and climate modeling, geodetic and geophysical expertise, coastal dynamics, coastal geography, coastal engineering, behavioral and institutional analysis and risk management and climate adaptation. SeaLevel is expected to advance integrated research across natural and social sciences and holds the potential to significantly enhance the science base needed to cope with this grand challenge for society.

2 State of the Art

Coastal sea level rise is one of the key effects of anthropogenic global warming, with far-reaching consequences for all coastal societies around the world (Milne et al., 2009). The level and severity of related societal impacts on low-lying coastal regions and islands will fundamentally depend on the detailed amount and the rate of coastal sea level change, on the availability of predictions accompanied by uncertainty information, on the natural response of the surrounding coastal system to those changes, but also on the way societies choose to adapt to sea level change - technically, economically and politically. Many of the respective considerations inevitably have to be local in nature, involving sustainable coastal development, integrated coastal management, coastal protection, damages, economic slowdown, changes in biodiversity, and health issues. Social sciences aspects of sea level research therefore have to be approached in a very local way, e.g., due to available scientific information, resources, economic power, and the level of local governance. However, local sea level change fundamentally depends on processes taking place remotely, making coastal sea level studies inevitably a global problem. Moreover, local societal impacts of sea level change can advance to global dimensions (e.g., trading and migration).

Local sea level is directly or indirectly affected by all components of the climate system, including the ocean, atmosphere, cryosphere, solid Earth and terrestrial hydrology (Fig. 1), but also by local human interventions (e.g. Becker et al., 2009). However, the relative contribution of individual processes to regional or local sea level change strongly depends on the spatial and temporal scales under consideration. Besides climate processes, local vertical movement of the sea floor can likewise influence coastal sea level in a severe way (e.g. Nicholls and Cazenave, 2010), and requires addressing geological processes (e.g., tectonics, isostatic adjustment, geomorphology), but also human activities such as ground-water extraction.

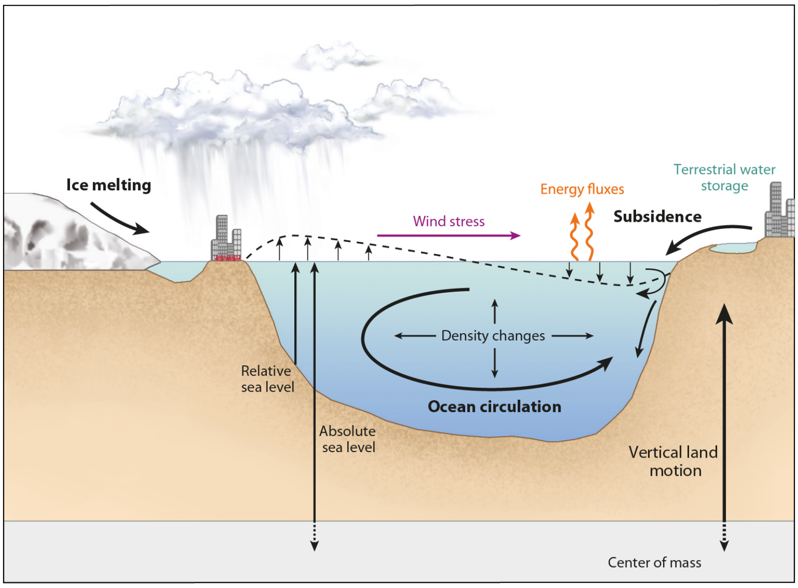

Fig. 1: Processes influencing regional sea level (besides global mean sea level change) are associated with: dynamical variations of the ocean circulation; a static response to atmospheric pressure changes; mass variations in the Earth system, notably an isostatic adjustment of the Earth's crust to past and present loadings; changes in polar ice masses; and changes in continental water storage. Local changes are also affected by vertical motion of the sea floor due to earthquakes, subsidence, or anthropogenic influences, such as ground water withdrawal (after Stammer et al., 2013).

Significant progress in understanding trends in global mean sea level has been achieved over the last decade (Church et al., 2011). However, fundamental gaps remain in our quantitative understanding of processes leading to coastal sea level changes in the past, in our ability to project coastal changes into the future (Church et al., 2014) and in our ability to use this information for guidance of the coastal community. A dedicated scientific program is required that identifies and quantifies processes leading to coastal sea level change, and that provides comprehensive information on the interactions of socio-economic developments with geophysical processes and climate modes, related societal responses, resilience capacities, and preparedness for undertaking adaptation measures, schematically illustrated on the title page graphic. Only such a program jointly involving scientist from the climate and coastal research communities can provide the scientific basis for a well-founded investigation of adaptation strategies to sea level change.

2.1 Human dimensions of sea level change

Sea level rise is threatening coastal societies with a large range of socio-economic consequences. This includes a reduction or loss of vital coastal ecosystem services such as storm protection through mangroves or loss of biodiversity; damage to critical infrastructure (e.g., transport and communication networks, power plants and grids, military facilities, etc.) and resources along the coast; loss of human life and health impacts; forced displacement due to land-loss and storm surge risk. The vulnerability of coastal societies and their potential adaptive capacity to changes in sea level thereby depends both on the magnitude of local sea level changes as well as on the human responses to those changes in addition to other drivers such as socio-economic development.

Most of future climate-related socio-economic impacts of sea level change are expected to interact with and to aggravate already existing coastal issues (Nicholls et al., 2007; Wong et al., 2014; Brown et al., 2014). Specifically, sea level change will further exacerbate coastal erosion and inundation hazards in many regions of the world (Hinkel et al., 2013). Regions currently most affected by sea level change include deltaic and low-lying coastal areas as well as small islands (e.g. Nicholls and Cazenave, 2010). Of those, densely populated and heavily farmed delta plains and coastal low-lands will become even more vulnerable to sea level change if combined with various environmental and anthropogenically altered hydrological patterns, soil erosion, agriculture, industrial development, and urbanization, e.g. alterations in the corresponding river systems. Socio-economically, the areas most threatened are rapidly growing coastal mega-cities in delta plains such as the Asian cities of Shanghai, Hong Kong, Bangkok, Manila and Jakarta (McGranahan et al., 2007; Hallegatte et al., 2013; Yang et al., 2014). The extent of the impact will depend on the rate of sea level change and the natural response of the coastal systems but also on the technical, economic, and political pathways which societies choose to adapt and on the interaction patterns between social agents, including conflict and cooperation. In addition, water withdrawal, oil/gas extraction, land use change, or coastal developments directly affect relative sea level change. For small island states, the most evident problems of sea level change are coastal land inundation, submergence, and saltwater intrusion (Ratter, 2008; Fenoglio-Marc et al., 2012), calling for an integrated coastal protection against multiple risks (Link, 2014).

To address the human dimension of sea level change and to promote adequate responses it is necessary to better understand human-environment interactions in the context of sea level rise, existing coastal issues, socio-economic and other stressors. This includes researching how coastal societies have been able to adapt to past sea level changes, for example in those coastal cities that have subsided by several meters during the last century (Nicholls, 1995). This also includes improving integrated coastal impact models to simulate future impacts under a range of adaption strategies and sea level rise scenarios. Regional to global sea level change information need to be provided at the coastlines, including the full range of uncertainty across multiple models and assessment methods. Further, governments, stakeholders, and local inhabitants need to be provided with this information and tailored decision-analytical frameworks in order to make informed decisions for future development.

Largest uncertainties in coastal sea level rise projections presently originate from uncertainties in polar ice sheet dynamics, glaciers, and the related mass input into the ocean, the future heat uptake and the regional response of sea level on basin to coastal scales to climate forcing. For quantitative coastal zone management studies, respective signal and uncertainty measures have to be propagated from the large spatial scale down to coastal locations and targeted at the specific kind of decision a coastal manager is facing. Coastal sea level projection studies are truly global and interconnected problems and require investigating sea level on multiple space and time scales in conjunction with an analysis of the requirements from local coastal risk management. When talking about local sea level change, we must take into account that even human interventions itself may change the sea level locally dramatically with severe impacts for coastal communities. This has to be regarded when planning for future.

2.2 Recent and future large-scale sea level changes

Since the end of the 19th century, global mean sea level is estimated to have risen by about 20 cm, and the rise appears to have accelerated during the past two decades (Rhein et al., 2013). The 2013 IPCC 5th Assessment Report (AR5) projected a global mean rise of ~50 +/-20 cm by 2100 for a medium warming scenario (Church et al., 2013); however, because of the large thermal inertia of the oceans, sea level will continue to rise during several centuries (IPCC, 2013). While the contribution of glacier and ice sheet mass loss to global sea level change already exceeded the contribution from ocean warming over the last decades (Church et al., 2013), space-based observations revealed that polar ice sheets are now losing mass at an accelerated pace (Shepherd et al., 2012). This suggests an even further increase of the cryosphere relative contribution to sea level rise in the future.

Regional contemporary sea level changes on interannual-decadal time scales appear to be mostly steric in nature. Much of the associated anomalies in heat and salt content can be explained by redistributions of the pre-existing water masses, i.e., linked to adiabatic advection associated with changes in ocean circulation (e.g., Schwarzkopf and Böning, 2011; Fukumori and Wang, 2013). Advective changes naturally involve both thermosteric and halosteric contributions; their relative role can vary widely depending on the regional temperature–salinity relationship (Köhl and Stammer, 2008; Durack and Wijffels, 2010). The contribution of climate modes to sea level changes will distinctly differ in the two study regions, with North Atlantic Oscillation (NAO) impacts dominant in the North Atlantic and on the European Shelf. In contrast, South-East Asia will be affected by several competing modes, such as El Nino-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), but also Southern Annual Mode (SAM) (see Appendix 2 for a list of abbreviations). Finally, climate modes are expected to change in the future and thus, it is required to quantify the anthropogenic impact on a changing climate background state and associated oscillations.

The main driver of ocean circulation changes on interannual-decadal time scales is wind stress through various dynamic processes (e.g., Ekman pumping, planetary waves, coastal upwelling). In turn, much of this wind-driven variability is related to climate modes, such as ENSO, PDO and NAO. The dominance of such internal redistributions to local sea level changes represents a major challenge for identifying the regional imprints of trends in the net heat and freshwater (and, see below, mass) input into the ocean, i.e., the anthropogenic effects responsible for much of the global mean sea level change. Corresponding spatial patterns present large decadal/multidecadal fluctuations mostly due to internal variability of the climate system (Stammer et al., 2013).

Satellite altimetry has given ample evidence that contemporary sea level changes in many regions of the world ocean are governed by vigorous short-term fluctuations (Fig. 2b), so that the spatial patterns of sea level trends on interannual-decadal time scales deviate widely from the global mean (e.g., Meyssignac and Cazenave, 2012). However, because of sparse data coverage by tide gauges, evidence of pre-altimetry regional sea level changes is incomplete in its geographical coverage. Longer-term reconstructions thus need to combine tide gauge records with statistical information on the dominant spatial modes of ocean variability or ocean circulation modeling (with and without data assimilation). Such reconstructions (Fig. 2a) provide preliminary estimates of evolving past spatial sea level pattern (Köhl and Stammer, 2008; Wenzel and Schröter, 2010) and allowed investigating links between coastal erosion and sea level change at sites remote from available tide gauge sites (Yates et al., 2012).

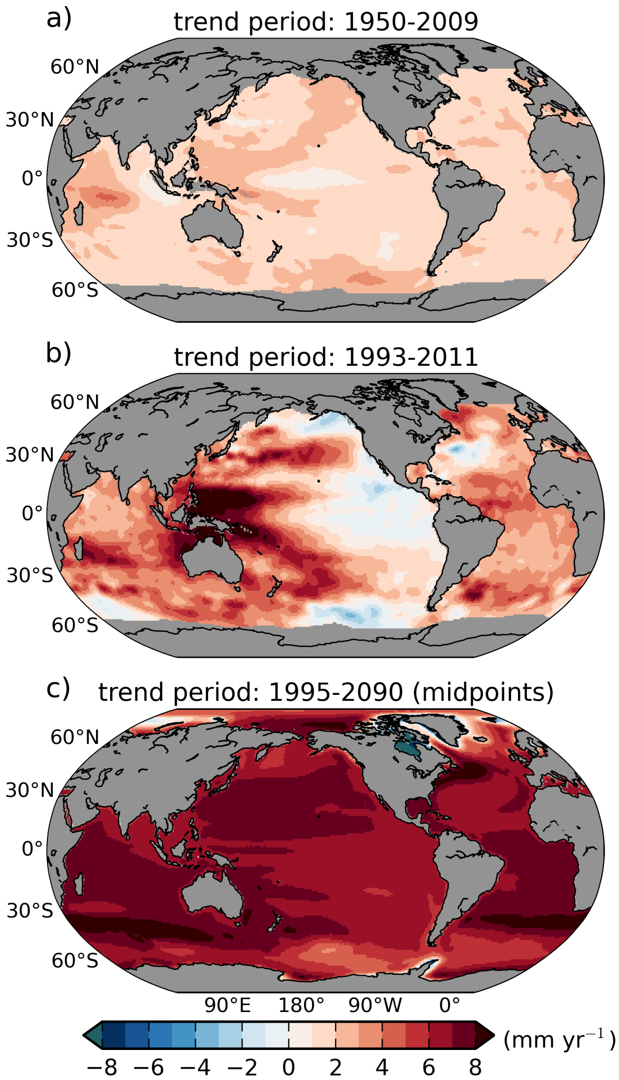

Fig. 2: (a) Reconstructed sea level change since 1950 obtained from an assimilation of the available network of long-term tide gauges with a global ocean model forced by atmospheric reanalysis products (Church and White, 2011). (b) Distribution of sea level change observed by satellite altimetry between 1993 and 2011 (from Stammer et al., 2013). (c) RCP 8.5 high-end ensemble mean net regional sea level change projection, between 1986–2005 and 2081–2100 (in m) which includes contributions from atmospheric loading, land-ice (glaciers and ice sheets), GIA and terrestrial water sources. Note that projected regional changes deviated strongly from a global mean estimate and in some regions can even be negative (after Slangen et al., 2013).

Previous studies suggest that (a) the global sea level change has been far from uniform even over time periods of 50 years or longer, (b) the spatial patterns of change differ between interannual and multi-decadal periods, and (c) the results obtained from different models and methods show non-trivial deviations, indicative of significant remaining uncertainties related to the underlying choices of model configurations and synthesis methodologies. While anthropogenic effects appear secondary at present-day interannual-to-decadal periods (Fukumori and Wang, 2013), their impact on regional sea level patterns is expected to increase over longer time spans. For instance, possible future trends in the Atlantic Meridional Overturning Circulation are expected to lead to major contributions to the sea level change along the coasts of the North Atlantic (Landerer et al., 2007; Lorbacher et al., 2010).

2.3 Ocean – ice sheet interaction

The interface between oceans and ice sheets plays an important role in the future melting of ice sheets. However, the processes occurring at this interface are only poorly understood and the interface is therefore not well represented in climate models (Joughin et al., 2012). Changes in ocean dynamics and heat supply lead to thinning of ice shelves and subsequently reduced buttressing, causing an acceleration of the draining ice streams (Joughin et al., 2012). Increased ice discharge also contributes to the thermo- and halosteric sea level change through melting icebergs distributed by ocean currents. Ice sheet instability, occurring from the retreat of grounding lines of marine ice sheets, is a second factor that influences regional sea level change. Evidence is emerging that the accelerated melting and retreat of glaciers and ice sheets contribute significantly to recent and future sea level change (Rignot et al., 2011). However, our understanding of contemporary and future contributions from ice melt to regional sea level change is only rudimentary. To make progress, we need to investigate: (1) what are the changes in the ocean circulation and respective transports of warm water onto the continental shelves; (2) what is the response of ice sheets to this warmer water and their internal variability; and (3) what is the solid Earth response to ice sheet mass loss? Answering those questions specifically requires investigating the ice-ocean interaction, grounding line dynamics and calving of outlet glaciers, as well as the ocean dynamics in fjords including ventilation, plumes and the mechanisms to transport warm deep water onto the shelf, the response of the solid Earth to ice load changes and self-gravitation (e.g., Hellmer et al., 2012).

2.4 Solid Earth sea level change contributions

For quantitative projections of regional sea level change we need to quantify factors arising from the visco-elastic response of the solid Earth to ice/water mass redistributions (Glacial Isostatic Adjustment - GIA), ongoing land ice discharge, changes of land water storage and river runoff and the regional evolution of coastal morphology due to sedimentary transport processes. Corresponding deformations of ocean basins and gravitational changes from these factors produce regional changes in sea level that fundamentally affect remote coastlines. However, in existing climate projections, only preliminary attempts have been made to account for those effects (Slangen et al., 2014), although they are expected to become stronger in their spatial pattern than observed in present day internal sea level variability (see Fig. 2c). It was only recently hypothesized that the effects of viscoelastic deformations of the Earth's lithosphere on regional sea level could be of particular importance for the reconstruction of paleo-sea level distributions, but also for projections of future sea level change in response to natural and anthropogenic changes in the distribution of water between land and ocean.

In certain areas of the ocean, the steric nature of regional sea level change is superseded by mass-related effects. The separation between both effects is an important step in detecting anthropogenic effects on sea level. Apart from the steric adjustments associated with changes in the thermohaline circulation and atmospheric feedbacks (Stammer et al., 2011), redistributions of water mass between the cryosphere, continent and the ocean, may be associated with motions of the Earth's surface and changes in the geoid and are formulated in the sea level equation (Farrell and Clark, 1976). Furthermore, they may affect the Earth's inertia and rotation, which produces an additional sea level response (Milne and Mitrovica, 1998), both processes that need to be quantified. In addition, basin-scale gravitational effects related to present-day mass redistributions external to the ocean (atmosphere, hydrological storage; e.g., Vinogradova et al., 2010; Jensen et al., 2013) may mask other effects in coastal oceans and also need to be quantified. At present times such a separation is not possible; however, larger effects related to mass redistributions are expected in response to future releases of freshwater from melting glaciers (Gardner et al., 2013) or polar ice sheets (Shepherd et al., 2012) and it therefore has to be anticipated that this process will be an important one in the future for any coastline.

2.5 Shelf sea dynamics and storm surges

Quantitative projections of future coastal sea level changes and an accurate assessment of socio-economic impacts of high-end sea level and extreme events demand to improve our detailed understanding of the imprint of all those effects on local sea level. Extreme events often induce damaging morphodynamic changes and coastal erosion. Essential for the use of sea level information as part of coastal management is the availability of likelihood information and uncertainty measures. For this purpose, we need to propagate the full error information and probability density functions from the global scale or remote location to any coastal locations together with sea level information itself, be they caused by ocean and climate dynamics, residing in the solid Earth, or originating from the cryosphere and hydrology. However, estimates from existing climate model projections (CMIP5) suffer dramatically from the lack of all processes involved. This includes the lack of spatial resolution of the ocean model components required to simulate shelf sea and coastal processes (1°-2°, vs. 1/10° and better required for regional and coastal simulations), but also the lack of pertinent physics, including coastal and shelf sea dynamics. Consequently, sophisticated regional downscaling efforts of the large-scale climate sea level signals are required to assess vulnerability and potential resilience capacities. In addition, local water withdrawal and/or land use change also affect local relative sea level change.

Already Denbo and Allen (1987) have shown that the characteristics of the large scale response of coastal sea level to fluctuations in wind stress can be very variable with latitude and in time, revealing the influence of many coastal dynamical details. More recently, Dangendorf et al. (2013) investigated sea level trends derived from the North Sea, North Atlantic and Mediterranean Sea tide gauges and showed that regional and local atmospheric forcing is partly responsible for the observed regional patterns of sea level change and to some extent also to regionally dependent acceleration in sea-level rise during the 1990s. Along the western European coast, tide gauge records show significant decadal variability (up to 15 cm) and a high correlation with the NAO and among themselves at decadal periods (Calafat et al., 2012). Boundary waves may propagate thousands of kilometers poleward and raise sea levels also in the North Sea (Dangendorf et al., 2014). The baroclinic nature of these signals provides important information about required horizontal resolution (<20km) of downscaling experiments. Similar contributions from all relevant climate modes, e.g. in South-East Asia originating from ENSO, PDO, SAM, of IODM, need to be quantified for our study regions, for which alongshore wind and wave propagation could be major contributors to coastal sea level variability.

3 Scientific Objectives and Program Structure

3.1 Scientific Objectives

As its central scientific objective, SeaLevel aims to perform an integrated analysis of climate-related sea level change and associated coastal human-environment interactions with a focus on two study regions: the North and Baltic Seas and the Island States of South-East Asia. These regions have been chosen to understand how coastal vulnerability and sea level rise response strategies vary in distinctly different cultural, political and socio-economic contexts, taking into account also social aspect of sea level rise impacts on Asian coastal megacities.

Reaching the program's objective requires greatly improved understanding of many aspects of regional sea level change, ranging from processes influencing sea level on the global and basin scale to geophysical processes acting on a regional to local scale as well as social processes related to human-environment interactions. This will be realized by (1) improving the physical knowledge base of regional climate related sea level change, (2) improving projections of sea level change on a regional-to-local scale, (3) investigating which socio-institutional factors enable or hinder coastal societies to cope with changing sea levels, (4) determining the natural and social coastal systems responses to future sea level change, and (5) assessing strategies to adapt to sea level change under given technical, economic, cultural, social and political constraints. To perform those integrated analyses, sea level change information (local sea level projections, storm surges, waves and extremes), uncertainty and risk measures need to be provided at their coastlines.

The proposed program aims to regionalize large-scale climate-related sea level change information on time scales up to 50 years. For a complete understanding of past, contemporary and future coastal sea level change, we need to quantify at the coast lines the contribution from climate-related factors due to changing atmospheric forcing (including wind stress) leading to changes in the ocean circulation and associated non-uniform thermo- and halo-steric expansion of sea water, in addition to a redistribution of mass. We will investigate regional sea level change predictability for our coastal study areas, derive respective uncertainty information and transform this information into sea level change relative to coast lines by merging dynamical sea level information with responses expected from the solid earth and shore line due to hydrological and sediment transport processes. All this information will be used to investigate socio-economic implications and interactions of regional sea level change and to simultaneously analyze the awareness, adaptation needs and responses of coastal communities as well as risk management decisions to be implemented in the study regions. Drawing from previous experiences in the South Pacific, the Indian Ocean, and the North and Baltic Seas, we aim to compare developed and developing coastal and island nations in different cultural settings in terms of regionally specific effects, vulnerabilities, resilience, adaptive capacities and response strategies to deal with sea level change. Results from these investigations from WP C will feed back to WPs A and B to further improve sea level rise projections for the use of coastal communities.

All studies performed as part of the SPP will be done in a two-way approach and will be performed interactively, involving the communication of sea-level information to coastal management users; at the same time the process will inform sea level scientist about decision making processes to improve sea level information for decision making processes. The SPP will create a knowledge basis for quantitative coastal zone management studies and will greatly advance our understanding of processes influencing regional sea level from global to basin scale, on regional interactions between the open ocean, shelf sea, ice sheet boundaries and morphodynamics.

3.2 Program Structure and Networking

SeaLevel is organized along three work packages, which differ according to their spatial scale, their geographic foci but also with respect to the required participation from natural or social sciences. As indicated in the schematic on the title page and detailed in Fig. 3, these work packages are all concerned with providing sea level information at coastal locations and studying the interactions between sea level changes and coastal societies. To foster interactions, **SeaLevel** work packages were planned around topics, not around disciplines. Although the focus of the work is on future decadal sea level changes, some aspects of the investigations, concerned with identifying relevant processes from past observations and documentations in geological records, require looking backward in time to understand potential future processes.

WP A will analyze **the mechanisms of sea level variability** with primary focus on processes leading to spatially highly inhomogeneous pattern of regional seal level change on time scales of up to 50 years. The WP will provide a comprehensive understanding of the natural and anthropogenic factors governing regional sea level variability. Respective work will include oceanographic, geodetic and cryospheric research on regional sea level pattern and will also address terrestrial hydrological contributions. We will determine the origin of regional sea level changes at decadal to centennial time scales and identify the mechanisms causing coastal sea level changes on decadal time scale. To reach these goals the WP has to address also basin-scale to global data quality issues of in situ and satellite data. Results from WP A will provide knowledge of processes leading to sea level changes in the past, today and in the future and will provide uncertainties in projected components. Such information is required as a boundary condition for coastal systems and their change on decadal to centennial time scales. Output from WP A will feed directly into WP B where an improved knowledge base will be created for coastal sea level change information with focus on the selected study regions. Output from WP A will also feed directly into WP C by providing regional climate information.

WP B is concerned with the establishment of a scientific basis for obtaining reliable **local projections of sea level trends,** thereby improving the scientific basis for providing quantitative and detailed (high-resolution and high-end) **estimates of future coastal sea level changes in the two focus regions**. **WP B** will investigate the interaction of the large-scale ocean circulation with shelf seas and ice sheets on regional and local scale thereby downscaling climate related sea level information to coastal locations. It will provide new insight into small-scale processes related to the downscaling of sea level to coastal regions. The information will be merged with local geophysical processes controlling vertical motion of the solid earth and changes in coastline morphology. WP B thus involves regional studies to investigate specific geophysical processes relevant for coastal sea level changes, e.g. the relationship between ocean circulation and sea level changes in shelf regions, processes relating to interaction of ocean circulation and ice sheets, and sea level changes in specific coastal regions due to land movement (subsidence) and lateral inundation (morphodynamics) in interaction with regional sea level changes. New insight gained by WP B in terms of sea level change will feed into WP C by providing improved coastal sea level change scenarios for the selected pilot regions. Massive adaption measures (such as massive embankments) might contribute to changes in extreme sea levels. This in turn requires intensive work on explaining past changes in local sea level including those driven by human interventions.

WP C will perform an **integrated analysis of sea level change and human environment interactions** in the selected two study regions, and will identify sea level stressors, coastal impacts, adaption pathways and policies for the studied regions. This will involve an assessment of how coastal societies have coped with past coastal changes, the socio-economic consequences of future sea level changes to coastal and island societies, and the implications of possible regional and **local adaptation and risk management strategies** in sea level hot spots. WP C will also use and explore to what extent the sea level rise information generated in WP A and WP B is effective for analyzing large infrastructure and planning adaption decisions in the study regions. By answering questions about socio-economic implications, adaptation decisions and human–environment interactions, WP C will stimulate the creation of knowledge basis for quantitative coastal zone management studies. The insights generated in WP C will also be essential for directing and readjusting the activities in the other WPs to make their outcome more useful for coastal communities. It is therefore anticipated that during the first phase of the SPP, results from WP C will feed back into WP A and WP B in terms of new questions asked and information requested.

4 Work Program

In the following, details of the planned work program are summarized. An overview of the proposed work packages is given in Fig. 3. Initial work within WP B and WP C will start with pilot results currently available from observed changes in sea level or from CMIP5 model runs. During the course of the effort, results emerging from WPs A and B will become more sophisticated, also by taking into account early results from WP C, and will provide full uncertainty information, thereby enabling more quantitative investigations in WP C. At the same time coastal adaptation efforts fundamentally depend of "upper bounds" sea level information. Both topics will be approached jointly in WPs A and B. On the other hand the use of sea level information during decision making processes in WP C will feed back into WP A and B by optimizing sea level information for coastal management purposes. In essence, we consider WPs A and B to develop the scientific basis to estimate and predict the intensity of coastal sea level changes. WP C will initially provide an estimate of the effects of the interactions between socio-economic developments and the processes described in WP A and B, and determine the related damage potential on coastal societies, i.e., the sensitivity of our study regions to sea level change. Integrating the knowledge on intensity and sensitivity will in turn provide new insight about vulnerability and risk potential of our study regions.

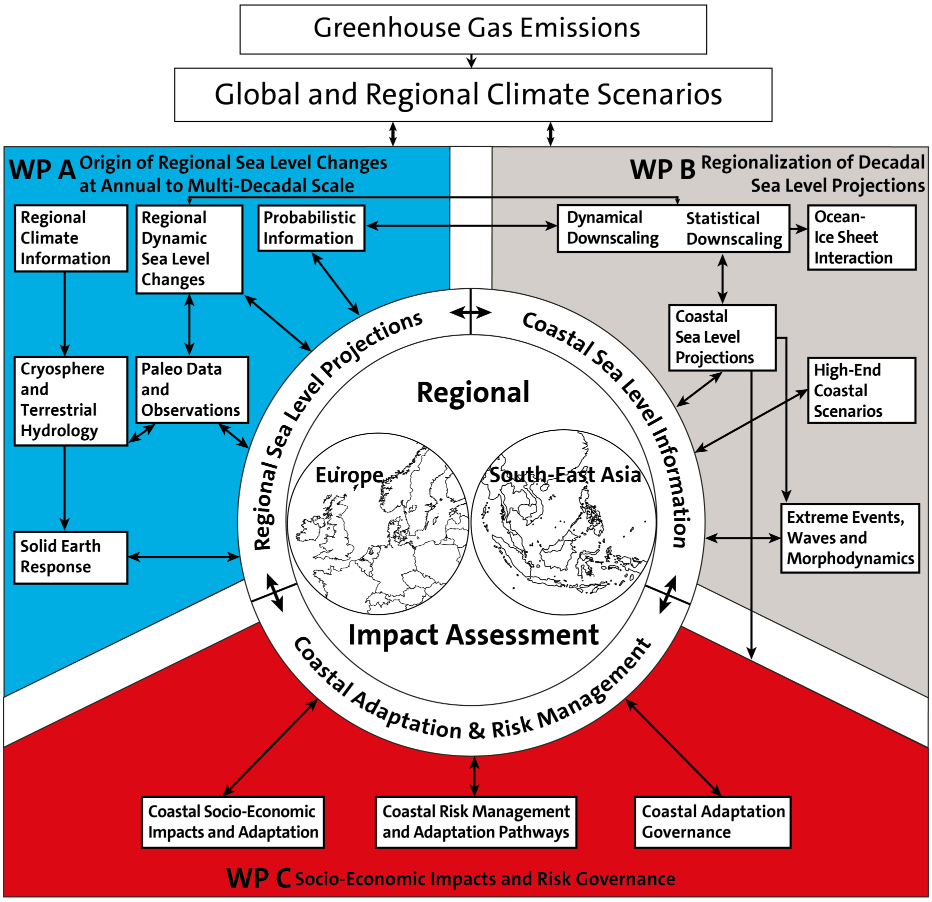

Fig. 3: The structure of the SPP work program. Shown are topics addressed in individual work packages and their interaction. Arrows indicate that all work packages contribute to the studies within the selected regions. Interactions between Work packages and their topics interact and integrate their knowledge through the regional impact assessment, displayed with the inner circle.

4.1 WP A: Origin of regional sea level changes at annual to multi-decadal scale

Challenges that need to be addressed:

To provide an improved detailed understanding of the dynamics and forcing functions of past and contemporary regional sea level changes, a challenge exists to identify all processes involved. Therefore, we need to understand the key processes leading to past, present and future regional sea level variability. Moreover, processes affecting regional changes are geographically diverse: while the tropical Indo-Pacific is governed by steric changes associated with wind-driven ocean circulation dynamics and related to modes of climate variability such as ENSO, PDO and IOD, trends at the North American and European coasts will also be affected by thermohaline processes. In addition, land motion and mass redistribution effects relevant to the tropical Indo-Pacific (local land motion due to volcanic activity; groundwater or hydrocarbon extraction; sediment compaction; ocean-shelf ice interactions governing the Antarctic ice sheets) are different from those affecting the North American and European coasts (post-glacial vertical motion; melting of the Greenland ice sheet). Furthermore, we need a comprehensive understanding for anthropogenic factors superimposed to natural variability before coastal change can be simulated and predicted on decadal to centennial time scales since both govern regional sea level variability as a boundary condition to coastal systems. This includes an improved reconstruction of the spatial patterns of regional sea level change, with particular emphasis on the decadal variability and trends during the last century.

Detailed uncertainty measures are essential for coastal zone coastal sea level change impacts, but are missing for regional sea level projections. Progress in this regard clearly necessitates an integration of hitherto rather disparate strands of research. As an example, large uncertainties in solid-Earth and gravity models have been identified recently as a major problem for determining the Earth's mantle viscosity structure, and thus also for quantifying the solid Earth‘ response to the last de-glaciation (GIA models); as a result, reconstructed paleo-sea levels in coastal regions can deviate from the eustatic value by more than 20 m due to continental levering or hydroisostatic correction (e.g., Lambeck et al., 2002;) with substantial variability due to the regional loading response, whereas this mechanism is negligible for many island sites (e.g. Jevrejeva et al., 2014). The contribution of present and future terrestrial hydrology has also been identified as major contribution to sea level projections over the next 50 years and beyond.

In recent years, satellite measurements in combination with the global ARGO profiling network have revolutionized the observational capabilities in this regard (Kusche et al., 2012). Nevertheless, many important data quality issues need to be addressed that are essential for improving our understanding of sea level changes and their representation in model simulations. This is essential for understanding ongoing and future sea level projections. The GRACE (since 2002) and GOCE (2009-2013) missions enabled the computation of high-resolution geoid models, and began to allow deriving changes in ocean mass. The full potential of those novel measurements for investigations of regional to coastal sea level changes has still not been reached. In combination with data from the new German-US GRACE-follow on mission (anticipated starting data 2017), a new view on satellite gravity and altimetry data is required for any sea level effort.

Work Program:

Approach: WP A will provide an integrated approach investigating changes in sea level due to changes in the ocean circulation and due to ice-sheet – sea level – solid Earth interactions. WP A will utilize a combination of analyses of historic and contemporary ocean observations, sea level reconstructions from geological archives, and global ocean models with enhanced process dynamics in relevant regions. The work program will thus involve elements with specific focus on these regional phenomena, but will also address aspects of a more global or generic nature.

The work program will be structured in four basic topics; work within each topic is expected to be addressed by several working groups as part of the SPP.

I) Origin of regional sea level changes at decadal-to-centennial time scale

- Quantifying of natural variability using observations and calibrated reconstructions; determining the role of climate modes (e.g., ENSO, IOD, PDO, SAM, NAO, AMO) and internal variability in general on sea level; quantification of the role of ocean circulation in shaping regional sea level changes; assessing the relative role of internal climate variability.
- Investigating of the causes of contemporary global and regional sea level change in the cryosphere, the atmosphere, and the ocean as well as in the terrestrial hydrological cycle; separating natural variability from anthropogenic forcing; attribution of regional sea level change to natural (e.g., solar, volcanic) and anthropogenic (e.g., tropospheric aerosols, greenhouse gases) radiative forcing agents.
- Assessing the role of the cryospheric and terrestrial water cycle in shaping regional sea level; understanding and reducing uncertainties in mass and steric contributions to contemporary sea level budgets at global, regional and local spatial scales.

II) Historic sea level estimates (paleo time scale)

- Performing an integrated approach to past sea level change by combining effects of ice sheet dynamics, ocean dynamics and feedbacks with the solid earth: Assessing processes that are involved in past ice sheet changes, including sea level-ice sheet feedback.

- Investigating self-consistent interactions between the models of ice, land, ocean, and atmosphere including ice and sea level histories over Holocene; generating a consistent sea level budget for different time periods.
- Refining regional earth structure by assessing lateral heterogeneities and non-Newtonian rheology affecting the loading response, considering sedimentary loading and compaction.

III) Sea Level Projections

- Separating of internal variability and anthropogenic causes of future spatial trend patterns; understand how changing oceanic conditions (circulation and sea level) affect the dynamics of outlet glaciers in ice sheets, e.g. due to advection of heat; determination of the patterns of sea level change originating from ocean circulation changes due to wind forcing, air-sea heat and freshwater fluxes; processes relating to the reaction of ocean circulation and sea level to melt water; effects of water mass changes in the deep ocean.
- Improving estimation of mass loss from ice sheets; quantification of the key driving factors; improved description of ice sheet dynamics and the feedback between the ocean and ice sheets; tipping points for Greenland and western Antarctica ice sheets; investigation of effects of continental ice mass changes and feedbacks from solid Earth load deformations.
- Determining limits of predictability of sea level as function of space and time scale and the role of changing climate modes for sea level predictions; provide reliable uncertainties for sea level predictions and projections, including those for ice sheets and glacier projections; understanding regional inter-model sea level spread in climate models due to change in ocean properties (temperature, salinity, circulation, mass distribution), forcing functions and ensemble size.
- Determining sea level uncertainty information and upper bounds of sea level projections from an analysis of multi-model and multi-approach ensembles of sea level projections.

IV) Observations and calibrated reconstructions

- Quantifying requirements for an optimal and integrated (satellite and ground based) sea level observing system; improve the observational record of mass balance estimates and sea level change in shelf sea regions (drainage basin scale); improvement of GIA models and separation of different contributions to mass loss; quantify mass loss based on natural system, intrinsic variability versus response to atmospheric/oceanic forcing.
- Participating in coordinated multi-method, multi-model reconstructions of regional sea level changes during the last century which will, in particular, be needed to quantify remaining uncertainties; complementing the analysis of sparse tide gauge records by exploring information residing in corals, salt marshes and other geological archives, and their potential use as proxy data for regional sea level on multi-decadal and longer time scales.
- Identifying weaknesses in the observational data set of paleo sea level change; supplementing geologic sea level indicators with geodetic data, while accounting for other contributors to these observations.

Expertise involved: Work will involve physical oceanography, climate physics, and paleoclimatology, expertise from glaciology, geophysical and geodetic communities.

Outcomes and Deliverables: All information required as input for projecting coastal sea level into the future with specific emphasis on the two selected study regions and ocean-ice sheet interaction regions. This includes uncertainty and upper bound estimates for each component leading to regional relative sea level at the coastline. Initial results obtained in WPs B and C will lead to a revision of the aspects investigated in WP A.

4.2 WP B: Regionalization of Decadal Sea Level projections

Challenges that need to be addressed:

To connect regional sea level variability, studied in WP A, with coastal impact assessment investigations, considered in WP C, major advancements are required in downscaling sea level projections from the basin scale to any coastal location under consideration, thereby also down-scaling uncertainty information resulting from various remote processes, e.g. in form of ice sheet probability density information. It also requires major advancements in understanding the interplay of resulting local sea level changes with extreme sea level events and with coastal morphodynamics. To this end, advancements in modeling on regional to coastal scale are prerequisite to dynamical linkages between the open ocean and coastal regions, thereby considering locally heterogeneous dynamics and non-steric effects of changing sea level over shelf areas (Landerer et al., 2007). We expect that in shelf seas, sea level should be strongly affected by the local circulation dynamics itself. Moreover, along coastlines, extreme events such as storm surges can exacerbate the effect of sea level rise. However, both processes are not quantified, making it difficult to date to connect basin-scale and regional sea level projections to coastlines.

Downscaling approaches can also involve statistical methods, which might be easier to implement in our case study regions. However, these approaches typically require an extended database to derive necessary statistical relations. Similar to the open ocean, we therefore also need to improve the observational coastal records to better assess shelf sea dynamics and coastal sea level changes, involving tide gauge and altimetric records (1) by extending the altimetric data base (e.g., Fenoglio-Marc et al., 2012) to the coast and (2) by improving the understanding of natural and anthropogenic induced land motion in tide gauge stations (Trisirisatayawong et al., 2011; Wahl et al., 2013).

Of fundamental interest for a reduced uncertainty of sea level changes in our coastal study regions is the local interaction of ocean currents and sea level with ice sheets, which has a strong impact on sea level projections of remote coastal regions. For this purpose we need to substantially advance our understanding of the physical mechanisms of ice sheet changes driven by ice-ocean interactions by regional or local observational and modeling analyses (Straneo et al., 2013). Moreover, modeling the contribution of ice sheet and glacier mass loss to coastal sea level requires an adequate representation of ice sheet dynamics and of changing grounding lines in models (Pattyn et al., 2013), calling for the development of full Stokes models with a high-resolution at the grounding line. Coupling ice sheets to the solid Earth's loading response and the related changes of regional sea level are a further factor influencing the dynamics of the grounding line and ice shelf (Konrad et al., 2013).

All coastal sedimentary systems are strongly controlled by feedbacks between water circulation and sediment transport through morphological features, such as subaqueous dunes or channels, coastal systems often show complex morphological responses to changes in sea level and ocean circulation as outcome of counteracting processes of sediment deposition versus erosion (Amos et al., 2010). Sea level change and extreme events (see below) therefore often induce morphodynamic changes, especially in deltaic regions where deterioration can be observed first in the submarine delta front (Plater and Kirby, 2012, Unverricht et al., 2013). However, on decadal and longer timescales morphodynamic models often suffer from clear limitations in reproducing complex morphological evolution (e.g. Chu et al., 2013 and refs. therein). To advance our understanding of the coastal evolution of our study regions, it is required to quantify and understand the sediment transport, erosion, deposition and preservation processes (that control coastal sedimentation from decadal to event timescales) as a function of changing sea level; at the same time we urgently need to improve morphodynamic models for those regions to allow quantitative predictions of those changes.

Finally, to advance the coastal management in our study regions it is necessary to improve projections of future sea level extremes, affected by extra-tropical storms (Woodworth et al., 2007) and by the increase in local mean sea level (Dangendorf et al., 2013). For many coastal regions with smooth topography a rising mean sea level will represent an increase in the frequency of storm surges, which have the potential to cause large economic and ecological damage when hitting insufficiently protected coasts (Hallegatte et al., 2011a, b). The estimation of changes in frequency and intensity of storm surges is, however, not straightforward, since they depend on many local parameters, sea level being only one. For coastal adaptation measures, knowing extremes of sea level change is crucial, as secular trends in sea level will most directly affect peaks in storm surges. However, to what extent secular sea level changes can be added linearly to surge changes (Woodworth et al., 2007) has to be investigated for various scenarios in our case study regions (Mudersbach et al., 2013). Previous model results point to a significant increase of storm surge elevations for the continental North Sea coast of between 15 to almost 25 cm (Woth, 2005). However, it has to be investigated whether this also holds in the North and Baltic Seas and for the Indonesian Archipelago.

Work Program:

Approach: WP B will combine observations and modeling to downscale regional sea level changes to shelf-sea and coastal regions, both dynamically and statistically. Respective work aims at improving our understanding of sea level dynamics in the two case study regions to improve our ability to predict or project coastal sea level changes there. Work will involve regional simulations with model systems incorporating high-resolution coupled atmosphere-ocean-wave models, including tide. Altimetric databases will be extended to the coast, to consistently link it with tide gauge/GNSS observations and solid Earth response models, thus bridging the spatial scales from regional to local, and merging historical long-term records with current sea level monitoring and future predictions. This task will be facilitated by new observation technologies of modern satellite altimetry sensors. At the same time, work will target detailed ocean-ice sheet interaction studies leading to an improved process understanding of ice sheet mass loss which is demanded by WP A. Concerning observations of ice sheet changes, three fundamentally complementary approaches exist: (1) the geometric approach, based primarily on satellite altimetry; (2) the input-output approach, which estimates the budget of surface mass balance and ice discharge using InSAR space techniques; and (3) the gravimetric approach using the GRACE and the prepared GRACE follow on missions.

The work program is structured in four basic topics; work within each topic is expected to be addressed by several working groups as part of the SPP.

I) Coastal Sea Level Projections

- Assessing processes contributing to coastal sea level changes; understanding the role of coastal and ocean interior processes on local sea level; understanding deviations between sea level trends in deep ocean and coastal regions due to shelf dynamics and effects of mass loading and self-attraction;
- Downscaling sea level projections for coastal locations, thereby quantifying ocean dynamic processes which show relevant impact to coastal sea level; reduction of uncertainties of coastal sea level projections by improving the description or parameterization of relevant processes in models; determining limits of predictability of sea level as function of space and time scale and the role of changing climate modes.
- Improving the observational altimetric/tide gauge records (also toward the coast) through reanalysis and homogenization efforts;

II) Feedback with Extreme Events and Morphodynamics

- Assessing the interaction between mean sea level changes and extremes; identification of future weather patterns that give rise to the most extreme storm surges and their possible relationships with large-scale circulation patterns; assessment of changes in the occurrence of large-scale patterns in ensembles of climate change simulations with global and regional climate models.
- Investigating morphodynamic response of coastal systems to sea level change, storm occurrence and river discharge; improve morphodynamic models to include processes relevant on decadal time scales; establish a physical knowledge base of coastal change on the scale of increasing relative sea level change; quantify the relationships between coastal land loss and the rate of sea level change by measuring and separating the components of relative sea level change due to subsidence (natural/man made), reduced sediment supply (from land/from sea) and sea level rise.
- Understanding the extent to which natural coastal systems are resilient to sea level change or can adapt to it by changes in the offshore and onshore morphology; estimate land loss through inundation for high-end climate scenarios in key regions; impact of anthropogenic actions on local sea level.

III) Sea Level - Ice Sheet Interaction

- Improving process understanding of the iceberg calving linking the open ocean though fjords and outlet glaciers to the ice sheets; Improved description of ocean-ice sheet interaction; understanding ice – ocean interactions.
- Developing improved representations of grounding line migration; quantifying the uncertainty of mass loss projections missing or poorly known topography and boundary conditions; providing parameterizations of basal melting and calving of outlet glaciers for coarse resolution models.

IV) Coastal Sea Level Information

- Providing reliable uncertainties for coastal sea level predictions and projections especially for the selected regions, including those for ice sheets and glacier projections; model uncertainties; missing processes; scenario uncertainties; internal variability;
- Analyzing present-day vertical land motion and their incorporation in the interpretation of regional sea level trends and mass redistribution; Correcting models for other processes contributing to regional land motion like groundwater and hydrocarbon extraction, sediment compaction, volcanism and tectonics.
- Communicating results from SeaLevel to use by respective coastal communities; Transitioning sea level variability and uncertainties from regional to local coastal scale, probabilistic information and return-period from combined effects of sea level rise and changes in extremes (e.g., storm surges).
- Downscaling full sea level uncertainty information and upper bound of sea level projections available from WP A to selected coastal locations; Using a multi-method approach to extreme-value sea level statistics.

Expertise involved: ocean, coastal and marine geology, terrestrial hydrology, cryospheric, geodesy, atmospheric expertise.

Deliverables: High spatial resolution coastal sea level projections, their uncertainties and extreme value statistics for study areas and in ice-ocean interaction regions separated by processes (warming, GIA, ice sheet, change in morphology, hydrology). Jointly with the assessment of sediment transport and hydrological processes and their variability in stabilizing coastal landforms, this will form an essential contribution of sea level change information as input to WP C.

4.3 WP C: Socio-economic Impacts and Risk Governance

Challenges that need to be addressed:

A diversity of approaches has been applied to assess the interactions of coastal impacts, vulnerability, resilience and adaptation (Nicholls et al., 2007; Harvey and Woodroffe 2008; Wong et al., 2014) including hydrodynamic models (Xia et al., 2011; Lewis et al,. 2011), morphodynamic models (Jiménez et al. 2009; Ranasinghe et al., 2012), geo-spatial mapping of exposed population, assets or geomorphological units (Dasgupta et al., 2009; Boateng 2012), biophysical vulnerability indices (Yin et al., 2012; Bosom and Jimenez 2011) as well as socio-economic indices (Cinner et al., 2011; Yang et al., 2014). While all of these approaches have contributed to raising awareness of the threats of sea level rise, they have been less successful in supporting adaptation for several reasons stressed in the coastal chapter of AR5 (Wong et al., 2014) and also the Belmont Challenge White Paper.

First, in many approaches adaptation is not explicitly and realistically considered. Vulnerability indicators, for example, are great for raising awareness, but less useful for supporting decision-making (Hinkel et al., 2009). AR5 highlights that only few coastal impact assessments consider adaptation and those that do, generally ignore the wider range of adaptation measures such as ecosystem-based protection options, accommodation options and retreat options (Wong et al., 2014). Assessing impacts without considering adaptation is problematic because this leads to implausible results. For example, many assessments of coastal inundation assume that development continues in the coastal flood plain under rising sea levels and no protection upgrade. In reality, societies will adapt. Growing flood risk would either lead to higher protection standards or divert new development to other locations and displace existing people and development without protection (Hinkel et al., 2014). Hence impact assessment needs to consider adaptation in the context of all relevant feedback of coastal human-environment interactions.

Second, there is a lack of approaches that assess socio-economic impacts and support adaptation decisions at broad regional scales (i.e., on the order of hundreds of kilometers of coastal length). Knowledge on socio-economic impacts is important because it allows responses, which improve the resilience of coastal societies. Hydrodynamic and morphodynamic approaches are available for local level planning but can generally not be applied at the broader scales involved in long terms adaptation decision making because these methods are data and resource intensive (Dawson et al., 2009).

Third, little attention has been paid towards aligning decision analytical frameworks with the particular coastal adaption decisions faced and sea level rise information. Coastal adaptation decisions differ in terms of properties such as tolerable levels of risk, or lead and lifetime of the options involved, and thus require different decision analytical frameworks (Hinkel and Bisaro, 2014). For example, lead and lifetimes of beach nourishment decisions range from one to several years whereas those of coastal protection infrastructure may range over several decades. Furthermore, the state-of-the-art techniques for coastal decision analysis have evolved rapidly from traditional benefit-cost approaches to novel approaches such as robust decision-making (Lempert and Schlesinger, 2000) and adaptation pathways (Haasnoot et al., 2012). Substantial research is needed to test and further refine these techniques to fit the specific circumstances of the particular decisions faced and to produce sea level rise information that fits this decision context. One particular issue thereby is matching demand and supply. Large scale coastal infrastructure investment decisions such as flood-proofing London during the 21st century, as prominently addressed by Thames Estuary Project 2100, require and apply upper bounds of changes of sea levels and extreme water levels (Lowe et al., 2009). On the other hand, AR5 WG1 authors, conclude that the current literature does not allow providing such upper bounds (Church et al., 2013).

Finally, empirical evidence has accumulated that even when options are analyzed to be suitable, this does not necessarily lead to action on the ground due to a range of cognitive, institutional and other barriers involved that prevent implementation (Moser and Ekstrom 2010; Moser et al., 2012; Wong et al., 2014). Prominent examples of such barriers in coastal adaptation are a lack of clear organisational responsibilities at the national and regional levels (Storbjörk, 2010), a lack of horizontal and vertical integration of policies relevant to coastal zone management (Brown et al., 2002) and the complexity and bureaucracy of government organizations (Stojanovic and Barker, 2008). In order to overcome these barriers, assessment thus must consider existing governance arrangements and their interplay at multiple levels of decision making as well as the context of existing issues, conflicting interests and complex inter-linkages between public and private decisions (Few et al., 2007; Urwin and Jordan, 2008; Hinkel et al., 2009; Geels, 2011).

Work Program:

Approach: WPC addresses each of the four challenges listed above. The work program is structured in three basic topics, which interact as described below. Work within each topic is expected to be addressed by several working groups as part of the SPP. A particular emphasis will be placed on comparative analysis of socio-economic impacts, adaptation strategies, associated risk management decisions and governance arrangements for socio-economic host-spots of coastal vulnerability such as the rapidly developing coastal megacities of Asia.

I) Integrated modeling of coastal socio-economic impacts and adaptation

This topic develops integrated models of human-environment interactions underlying sea level change, extreme events, impacts and responses of coastal communities including the consideration of novel adaptation options of coastal societies as well as increasing pressures of population and economic development in coastal areas (Nicholls et al., 2007; Scheffran et al., 2012; Scheffran and Remling, 2013; Wong et al., 2014; Brown et al., 2014). A special emphasis will be placed on large-area assessments for the two study regions as well as socio-economic impacts. Towards these ends a range of analytical tools (GIS, complexity science, simulation models, agent-based models and social network analysis) shall be applied to project the consequences of the sea level rise scenarios developed in WPA and WPB as well as the adaptation strategies taken including adaptive risk management as well as various forms of social interaction. This analysis will also be informed through the behavior and risk perception analysis conducted under Topic 3 described below.

- For coastal erosion this will include modeling the links between human coastal management and shoreline dynamics (van den Berg et al., 2011) by, for example, coupling economic models of beach and shore nourishment decision making with coastline dynamics model (e.g., McNamara et al., 2011; Link et al., 2013; Hinkel et al. 2013).
- For coastal flooding, models need to be improved on the response of individual households to increasing coastal flood risk (e.g. migration or accommodation) as well as on societal responses in terms of protecting against rising flood risks in the context of socio-economic development.

II) Coastal risk management and adaptation pathways

This topic focuses on supporting coastal risk management decision making through developing and applying suitable decision analytical frameworks and sea level rise and extreme water level information. The integrated models developed in Topic 1 will be combined with adequate decision-making frameworks in order to assess costs and benefits of adaptation options and to develop multiple adaptation pathways in response to (anticipated) impacts of sea level change. Decision analytical frameworks must thereby take into account the full range of inherent uncertainties in the processes of sea level change and socio-economic development in order to avoid the risk of maladaptation (Eriksen et al., 2011).

The focus will lie on large investment and long-term planning decisions within the two study regions. Work will thereby proceed from a particular decision identified in a study region to selecting and adjusting appropriate decisions-making frameworks (e.g. benefit-cost analysis, cost-effectiveness analysis, multi-criteria analysis, robust decisionmaking adaptation pathways etc.) and sea level rise information. This will be a highly interdisciplinary and interactive exercise amongst risk management and governance scholars that articulate sea level information needs based on the particular decision context on the one hand and scholars of climate and geosciences that articulate what can be provided based on the state-of-the art science on sea level change on the other hand. Results of this exercise will be used to further shape the research conducted in WPA and B in later stages of the SPP.

III) Coastal adaptation governance

Research under this topic will investigate how governance arrangements (formal and informal institutions such as policies, rules, norms and conventions) as well as the perception of coastal risks enable or hinder coastal adaptation. Research will also explore the design of effective governance arrangements and policies to overcome prevailing adaptation barriers. Research may operate both at the household-level focusing on cognitive barriers and awareness raising as well as at multiple levels of jurisdiction involved in coastal adaption planning and focusing on institutional barriers. Existing policies, strategies, economic dynamics and institutional settings will be investigated for different geographical, social-economic, political, cultural settings in order to understand the context for dealing with human-induced threats to coastal areas. These results will be fed back to Task 1 in order to improve adaptation models in the assessment of socio-economic impacts. Research will be case study based; data will be gathered through document analysis, interviews, questionnaires and focus groups.

A particular focus will be placed on addressing the following questions:

- How have socio-economic and physical stressors (sea level change being one of them) and their interactions affected the vulnerability and resilience of coastal communities in the past and through which kind of strategies have communities been able to cope with or adapt to these stressors (Holdschlag and Ratter, 2013)?
- Which social-institutional factors hindered or promoted learning, capacity building and adaptation during coastal climate-induced disasters (e.g. Hurricane Sandy, Typhoon Haiyan, etc.)?
- What is the role of cultural framing, perception, experience, information and learning of communities in the building of local knowledge on and adapting to sea level rise? How does regional sea level change transform social patterns of local coastal communities, including the social basis of adaptive capacity, the structure of social networks, and the role of collective responses (Bohle et al., 1994; Adger, 2003; Barnett and Adger, 2003).
- Which types of governance arrangements across multiple levels may incentivize public and private actors to collectively address the challenges of sea level rise and to transform vulnerable regions into climate-resilient coasts?

Expertise involved: Led by expertise in social sciences (incl. integrative geography, sociology, environmental economics, political science, risk management, international law, and communication science), the SPP will combine the expertise available from oceanographers, geophysicists, geologists and different social science disciplines.

Deliverables: Integrated coastal impact models and assessments of the socio-economic impacts and adaptation strategies for the two study regions and using the scenarios of WP A and WP B. Decision analytical frameworks, required sea level rise information and adaptation pathways for a couple of major infrastructure and planning decisions in the study regions. This will inform the refinement of the work program under WP A and WP B in the second phase. Coastal governance arrangements and policies for coastal adaptation and integrated risk management, building on the scenarios of WP A and WP B as well as the results of Topic 2.

5 Meeting Review and Selection Criteria

5.1 Novelty in Germany and Internationally

The scope and breadth of the proposed program is unprecedented and with its strong socio-economic focus unique. Yet it encompasses all required natural science aspects of regional and local sea level projections, involving in a multidisciplinary context expertise from ocean and climate sciences, geodesy, and geography to address sea level change. Essentially, a novel platform for innovative and interdisciplinary cooperation tailored to explore new approaches to future regional sea level change and socio-economic impact studies will be created and will substantially advance the knowledge base required for improving coastal sea level projections. This novel knowledge base will be used inside but potentially also outside the SPP in pilot socio-economic and adaptation applications. The research community in Germany is well equipped and ready to tackle this important problem by providing proven expertise in all relevant natural and social science disciplines, combining knowledge from ocean and climate observations, ocean and climate modeling, geodetic and geophysical expertise, coastal dynamics and coastal community behavior and development options.

Not all aspects of coastal sea level change and its impacts can be approached through this SPP, specifically those unique to coastal engineering communities. However, the expected outcome of **SeaLevel** will have a lasting impact on the coastal communities by providing presently absent approaches and knowledge about coastal sea level projections using complex climate models, assessing the impact of sea level change on society, and understanding the complex interrelations between human and natural factors that shape coastal regions. As a long term goal, the SPP will enable new studies on societal impacts of sea level change and required adaptation measures, an innovation that otherwise would not be possible in the near future. It will also create an interface for an in-depth interaction with the coastal engineering community.

The problem of regional sea level change can finally be addressed at this point in time because of a recently established scientific basis to investigate this new aspect of climate change. This includes new observations of regional sea level. New possibilities also include an enhanced observational and paleo-proxy database and capabilities; improved and expanded capabilities for hydrographic observations; improved ocean models, including assimilation methods capable to aid and complement studies of past and ongoing sea level changes. In particular, improved complex coupled climate models now include many of the components of the Earth system (ocean, atmosphere, land and cryosphere), which are required to provide estimates of present day and future dynamical sea level changes. In addition, off-line estimates of sea level changes resulting from polar ice sheet mass loss and respective reaction of the solid Earth are available. Jointly those estimates can be used to start investigating regional sea level projections and to refine those for impact studies.

The study requires bridging expertise from natural and social sciences in a multidisciplinary context in an innovative way. **SeaLevel** therefore involves several natural science disciplines, which are concerned with the mechanism of sea level change (physical oceanography, geosciences and hydrology), its monitoring and observation (physical oceanography, paleoceanography, geodesy and marine geology), as well as social sciences disciplines, which address the interactions of socio-economic developments with geophysical processes and climate modes, as well as socio-economic impact of sea level change (geography, sociology, economics, environmental management and communication).

Because of its central societal importance, regional to local sea level change has been identified by the World Climate Research Program (WCRP) as one of their global challenge research themes in its project CLIVAR. Regional to local sea level change has also become an emerging issue in the recently published Fifth Assessment Report of the IPCC (AR5), and, in particular the lack of sufficient understanding that hindered its assessment. The proposed SPP will therefore be at the forefront of sea level impact studies, and will contribute directly and centrally to those international activities; at the same time it will greatly benefit from international knowledge exchange and program coordination of the WCRP.

5.2 Synergy – ways and means of planning cooperation

The scientific community has made substantial progress in studying the climate system over the last years. This especially relates to the global energy budget and associated changes in surface temperature. Sea level is an integral part of this discussion, which became obvious through the recent debate as to why global warming came to a halt during the last few years and where the missing heat is going. Due to its integrating character, global mean sea level became an important diagnostic tool in this ongoing debate, which also highlights the interdisciplinary nature of present day sea level research. In the case of socio-economic impacts of regional sea level change, it is even more obvious that an integrated approach to past, present and future sea level change is mandatory to make further progress in reducing uncertainties, and to advance the fundamental understanding required for a quantitative assessment of future regional and local sea level changes in the context of a range of suitable response strategies. This requires an improved cooperation between all involved disciplines from natural and socio-economic sciences. Collaborations already exist between the involved groups and fields, which will be further strengthened and advanced, specifically toward interactions with social sciences. **For this purpose we will strive to allocate funds equally between the three work packages**. **SeaLevel** is expected to substantially advance the field and will constitute the German national contributions to cope with this grand challenge for society.

Networking within the SPP will be established and monitored through the implementation of an executive committee representing all involved disciplines (similar to the applicant team of this proposal). Other means of interaction within the SPP will be annual meetings and other standard measures like a web page. To enhance the collaboration even further, various additional measures will be implemented; these will encompass dedicated workshops, topical working groups, postgraduate summer courses, working visits and an extensive visitor program. Workshops will be organized on SPP level, but also internationally to discuss and bring SPP results into the international context. In this context a WCRP/IOC sponsored conference on all interdisciplinary sea level aspects is already envisioned in 2016, following a similar conference held in 2006 in Paris. It can be anticipated that **SeaLevel** will play a substantial role in organizing this conference.

5.3 Ways of promoting early career researchers

PhD education and early career promotion is integral part of **SeaLevel**. All participating institutions are dedicated to foster innovative graduate and postgraduate education and career planning. This entails (1) building up junior research groups, (2) mentoring of postdocs, (3) structured graduate programs. The addressed three categories of early career researchers will participate in, and benefit from, funds being reserved for inviting guests, travel support and seminars, and retreats or meetings organized in the frame of **SeaLevel**. In addition, the following measures will be implemented to attract internationally outstanding students:

(1) **SeaLevel** will run a career oriented mentoring program for researchers at the postdoc level, which will be established based on and benefit from the experience with the ongoing mentoring program in CliSAP. Postdoctoral researchers employed as part of the SPP therefore select a mentor who will provide scientific and career guidance. In addition, specific measures may include the participation in

group assessment interviews or tailor-made lectures or practical training courses. The courses could address proposal writing (for e.g. DFG, EU-proposals), coaching, training (e.g. for applications, interviews), project management as well as leadership and teaching development. Postdoc, as well as PhD student positions will be announced internationally. **SeaLevel** anticipates that every entrained young researcher will spend a research visit at least at one foreign collaborating institute to broaden their scientific expertise and network to stimulate active career planning.

(2) **SeaLevel** will foster graduate education through the following elements: All PhD students will be advised through a panel system, usually representing the research within a work package, but also entailing at least one member from a different work package or a different discipline. All PhD students will spend a significant time abroad at a collaborating institution, ideally as part of a collaborative project. Those research visits will be fully funded through the SPP. Annual summer schools will join the students and post-doctorate researchers from **SeaLevel** with young scientists and experts at an international level.

(3) In addition, post-doctorate and PhD programs will be closely linked to and thereby expand the existing cooperation of young scientists, YESS (Young Researchers in the area of Earth System Science), established between the three excellence clusters on ocean and climate science in Bremen, Hamburg, and Kiel.

5.4 Gender equality measures

Equal opportunities start with creating a creative environment for outstanding research and a constructive work-life balance for both men and women. **SeaLevel** with its participating institutions will be fully compliant with the gender equality concepts and guidelines of the DFG. In particular, measures for a high level of equality to women and men and the improvement of the work-life balance will be implemented. The SPP will concentrate on five goals to promote gender equality: (1) Increasing female representation at all levels of the academic staff with a specific focus on early career stages, (2) promoting compatibility of gender issues, (3) fostering career awareness, (4) affirming progress, and (5) detecting shortcomings. These instruments towards these goals provide additionally support young researchers.

One of the strategic goals of the SPP is to further support equal opportunities at early career stages. Those efforts aim at both female and male PhD students, but with a focus on gender issues and gender specific communication structures. **SeaLevel** therefore intends to increase female participation at the PhD and postdoc level above the current average. Since the gender ratio substantially decreases with seniority, female researchers will receive specific support during the period after their post-doctorate phase, which has been identified as critical for women to continue their scientific career. Therefore, a specific mentoring program will support the career development of excellent female scientists during their post-doctorate period towards a professorship, independent research groups or other leading positions. To this end, the SPP will invite world leading female scientists to SPP annual workshops to provide young scientist the opportunity to learn from the experience of “role models”. Structural improvements such as on-site childcare during workshops and seminars are also envisaged.

Flexible work models based on individual life circumstances are essential in order to combine professional life and career development with family care, parental leave or sabbaticals. **SeaLevel** will completely support this approach. In addition, participating institutions are embedded in already existing structures and programs are being fully compliant with the concept proposed here. Additionally, support by student assistants will be granted for scientists during pregnancy for the time away from work, which will be supported as a measure for equality.

5.5 Outreach

Coordination of **SeaLevel** public relations will be associated with the project coordination (CEN) and will benefit from the expertise from ongoing large interdisciplinary projects (i.e. CliSAP). The overall mission of **SeaLevel** outreach is to promote general public understanding on all questions related to sea level change and associated impacts as well as providing a special toolkit for sea level communication. Efforts will include a continuously updated internet portal with a specifically developed E-book (“10 myths about sea level change”) as an attractive gateway. Further, the “SeaLevel Communication Office” (SeaCom) will serve as a point of contact for the press as well as the general public. The establishment of an internal communication platform (i.e. WIKI) is envisioned in order to foster the exchange of data and results, and to stimulate scientific discourse. Activities such as the participation in public information events or exhibitions (i.e. ‘Nacht des Wissens’ or ‘Open University’) are considered as essential to communicate findings to the public. The coordination office will also support all scientists involved in the program by dealing with individual requests for information, answering emails and internet blogs. In addition, all participating institutions are committed to contribute with existing outreach activities and resources to the **SeaLevel** outreach efforts. Close cooperation with Northern German States, governmental bodies and agencies on the EU level as well as WCRP and IOC is envisioned.

5.6 Coordination of the Priority Program

D. Stammer was elected coordinator of this effort in his capacities as CLIVAR SSG co-chair and co-chair of the WCRP/CLIVAR Global Challenge Group on “Regional Sea Level Change and Coastal Impacts”, but also in his capacity as lead author of Chapter 13 of the WG 1 AR5 on sea level change, where he was responsible for the section on regional sea level aspects. He has a proven track record in coordinating large efforts, including the US ECCO effort, the DFG Forschergruppe FOR1740, the BMBF projects North Atlantic, RACE, and Module-A of MiKLIP. For many years he was member of the DFG Senatskommission für Ozeanographie (SKO).

Within this SPP, the exchange of information and data will be fostered by engaging with data centers such as PANGAEA, ICDC and the DKRZ. Data as well as information will be published through established procedures at those centers. All **SeaLevel** results will be accommodated in one of those centers for long-time archiving. However, those centers will also play a fundamental role in exchanging data during the lifetime of the SPP.

6 Distinction to other Programs

6.1 Logical integration into the context of other, topically related funding activities

SeaLevel is firmly based on a longstanding German expertise in oceanography and geophysics/geodesy, which was build up as part of national and international activities such as CLIVAR, PAGES, Geotechnology Program (GEO:N), and in the context of space missions with German involvement/leadership such as GRACE of GOCE. **SeaLevel** also benefits from national activities performed in the context of CLIVAR over the last years related to observing and modeling the ocean circulation. At the national level, the SeaLevel theme was identified by Konsortium Deutsche Meereskunde (KDM) and the Deutsche Klima Konsortium (DKK) as one of the key challenges with national importance; the theme is also identified as important by the Senatskommission für Ozeanographie. There is no other activity that will address the posed questions on sea level. **SeaLevel** will be unique in integrating various communities, including social and communication sciences to address the impact of a rising sea level for society in a comprehensive and integrative way. We also note that subjects addressed by **SeaLevel** will be related to and benefit from the new BMBF effort on modeling the complete last glacial-interglacial cycle with comprehensive Earth-system models. On the EU level, the only related activity was ICE2SEA; it recently came to an end, did provide relevant information on cryospheric changes, but otherwise was very complementary to what is being proposed here; as a result, no equivalent funding landscape exists now on the EU level, in particular considering the breath of the approach proposed here. The same holds true on an international level.

6.2 International involvement and prominence

The overall topic of **SeaLevel** will contribute to the theme on sea level change identified by WCRP/CLIVAR as one of their global challenge themes for the years to come. Coastal vulnerability is one of the priority themes of the G8 Belmont Forum Initiative. All this indicates that sea level change and society are burning issues that have not been solved but belong to the frontiers of ongoing climate research. In this context, we note that two lead authors of Chapter 13 on Sea Level Change of the WG1 AR5 are members of the initiators of this priority program (D. Stammer, A. Levermann), as well as two coordinating lead authors from Chapter 3 (Ocean observation, M. Rhein), Chapter 5 (Information from Paleoclimate archives, M. Schulz) and one lead author from WG2 AR5 Chapter 5 on coastal impacts and adaptation (J. Hinkel). We expect that results from **SeaLevel** will contribute to these efforts in a pioneering way and that **SeaLevel** will provide substantial new insight that will benefit not only WG1 of the IPCC process, but also WG 2 and WG 3. The TIGA Working Group associated with the International GNSS Service (IGS), sponsored by the UNESCO/IOC/GLOSS, provides GPS-Data of many tidal stations to evaluate vertical land motion information. This information will be used as part of this SPP. As part of the Global Geodetic Observing Systems (www.GGOS.org) research groups regularly meet to discuss (their Theme 3) “Understanding and Forecasting Sea Level Rise and Variability”. The SPP will collaborate with this effort especially in the context of geodetic contributions to sea level change in coastal regions due to subsidence.

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Appendix 1: List of Prospective Participants

Name	Institution	Interest/Expertise
M. Becker	TU Darmstadt	Geodesy, geodetic observations
C. Betzler	Univ. Hamburg	Sedimentology, carbonates
C. Boening	GEOMAR, Univ. Kiel	Ocean dynamics and modeling
B. Braun	Univ. Köln	Geography, Social Sciences
Frau D. Dettmering	Deutsches Geodätisches Forschungsinstitut	Geodetic observations
C. Eden	Univ. Hamburg	Ocean and shelf sea dynamics
A. Eisenhauer	GEOMAR, Univ. Kiel	Marine Geosystems
Frau A. Engels	Univ. Hamburg	Social sciences
W. Elsner	Univ. Bremen	Economics, policy
Frau L. Fenoglio-Marc	TU Darmstadt	Geodetic observations, coastal altimetry
M. Flitner	Univ. Bremen	Socical Sciences
Frau U. Frömming	FU Berlin	Environment and coastal science
Frau M. Glaser	ZMT Bremen	Social Sciences, coastal ecosystems
T. Hanebuth	MARUM, Univ. Bremen	Sedimentology, coastal research
H. Held	Univ. Hamburg	Economic sciences, applications
A. Hepp	Univ. Bremen	Media Culture and Communic. Theory
J. Hinkel	GCF, PIK Potsdam	Coastal adaptation, social sciences
M. Horwath	TU Dresden	Geodesy, cryosphere
Frau B. Hünicke	HZG, Geesthacht	Regional sea level, coastal impacts
Frau A. Humbert	AWI Bremerhaven, Univ. Bremen	Cryosphere
H. Janssen	IOW Warnemünde	Social sciences
J. Jensen	Univ. Siegen	Coastal engineering
T. Kanzow	AWI, Univ. Bremen	Oceanography and climate dynamics
Frau D. Kieke	IUP, Univ. Bremen	Ocean processes
Frau B. Klein	BSH Hamburg	Shelf Sea oceanography
V. Klemann	GFZ Potsdam	Solid Earth physics

U. Kotthoff	Univ. Hamburg	Palynology, climate/sea level evolution
J. Kusche,	Univ. Bonn	Geodesy
S. Lindehorst	Univ. Hamburg	Sedimentology, climate/coastal evolution
M. Latif	GEOMAR, Univ. Kiel	Meteorology and climate dynamics
A. Levermann	PIK Potsdam	Cryosphere
P.M. Link	Univ. Hamburg	Social sciences, security
G. Lohmann	AWI, Univ. Bremen	Paleoclimate dynamics
J. Marotzke	MPI-Met Hamburg	Oceanography and climate dynamics
G. Massmann	Univ. Oldenburg	Hydrogeology, coastal aquifers
Frau Y. Milker	Univ. Hamburg	Micropaleontology, transfer functions
S. Mulitza	MARUM, Univ. Bremen	Paleoceanogrpahy
J. Müller	LUH Hannover	Geodesy, geophysics
J. Notholt	IUP, Univ. Bremen	Ocean processes, ocean observations
A. Paul	MARUM, Univ. Bremen	Paleoceanography, cryosphere
R. Pail	IAPG, TU München	Geodesy
Frau B. Ratter	Univ. Hamburg, HZG	Social sciences
Frau M. Rhein	IUP/MARUM, Univ. Bremen	Oceanography
M. Schäfer	IPMZ, Univ. Zürich	Communication and Media
J. Scheffran	Univ. Hamburg	Social sciences
M. Scheinert	TU Dresden	Cryosphere
G. Schernewski	IOW, Warnemünde	Coastal zone development
G. Schmiedl	Univ. Hamburg	Micropaleontology, transfer functions
M. Schnegg	Univ. Hamburg	Environment and coastal science
R. Schneider	Univ. Kiel	Geophysics
T. Schöne	GFZ Potsdam	Altimetric observations
W.-D. Schuh	Univ. Bonn	Geodesy
M. Schulz	MARUM, Univ. Bremen	Paleoceanography
B. Siebenhühner	Univ. Oldenburg	Ecological economics
N. Sneeuw	Univ. Stuttgart	Geodesy
D. Stammer	Univ. Hamburg	Oceanography and climate Science
K. Stattegger	Univ. Kiel	Coastal and marine geology
S. Traub	Univ. Bremen	Environmental economics
H. v. Storch	HZG, Univ. Hamburg	Coastal research, social sciences
A. Vafeidis	Univ. Kiel	Social sciences
M. Visbeck	GEOMAR, Univ. Kiel	Climate science
E. Zorita	HZG, Geesthacht	Coastal extreme events

Appendix 2: Acronyms and Abbreviations

AMOC Atlantic Meridional Overturning Circulation
AR Assessment Report
ARGO Global Ocean Float Network
AWI Alfred-Wegener-Institut für Polar- und Meeresforschung
BMBF Bundesministerium für Bildung und Forschung
BSH Bundesamt für Seeschiffahrt und Hydrographie
CAU Christian-Albrechts-Universität zu Kiel
CEN Center for Earth System Research and Sustainability
CLIVAR Climate Variability and Predictability
CMIP5 Coupled Model Intercomparison Project Phase 5
DKK Deutsches Klimakonsortium
DKRZ Deutsches Klima Rechenzentrum
ENSO El Niño – Southern Oscillation,
ESA European Space Agency
ESF European Science Foundation,
EU European Union
FOR1740 DFG Forschergruppe
GCF Global Climate Forum
GEOMAR Leibniz Institute of Marine Sciences
GEO:N Geotechnology Program
GFZ Geoforschungszentrum,
GIA Glacial Isostatic Adjustment
GISP2 Greenland Ice Sheet Project Two
GLOSS Global Sea level Observing System
GMSL Global mean sea level
GNSS Global Navigation Satellite System
GOCE Gravity field and steady-state ocean circulation explorer
GPS Global positioning system
GRACE Gravity Recovery and Climate Experiment
IAPG Institut für Astronomische und Physikalische Geodäsie
ICE2SEA Estimating the future contribution of continental ice to sea level rise
ICDC Integrated Climate Data Center
IGS International GNSS Service
IMPZ Institut für Publizistikwissenschaften und Medienforschung
InSAR Interferometric Synthetic Aperture Radar
IOC Intergovernmental Oceanographic Commission of UNESCO
IOD Indian Ocean Dipole
IOW Institut für Ostseeforschung Warnemünde
IPCC Intergovernmental Panel on Climate Change
IUP Institut für Umweltphysik
KDM Konsortium Deutsche Meereskunde
LUH Leibnitz Universität Hannover
MARUM Center for Marine Environmental Sciences, Bremen
MiKLIP Mittelfristige Klimaprognosen
MPI-Met Max Planck Institut für Meteorologie
NAO North Atlantic Oszillation
NASA National Aeronautics and Space Administration
PAGES Past Global Change Program
PANGAEA Publishing Network for Geoscientific & Environmental Data
PDO Pacific Decadal Oscillation
PIK Potsdam Institute for Climate Impact Research
RACE Regional Atlantic Circulation and Global Change
RCP Representative Concentration Pathway
SAM Southern Annual Mode
SeaLevel Regional Sea Level Change and Society
SKO Senatskommision Ozeanographie
SSG Scientific Steering Group
SPP Schwerpunktprogramm
TIGA Tide Gauge Benchmark Monitoring
TUM Technical University Munich
UNESCO United Nations Educational, Scientific and Cultural Organization
US ECCO US consortium **"**Estimating the Climate and Circulation of the Ocean"
WCRP World Climate Research Programme
WG Working Group
WP Work Package
YESS Young Earth System Scientists
ZMT Zentrum für Marine Tropenökologie