INTERGOVERNMENTAL PANEL ON climate change

IPCC Workshop on Sea Level Rise and Ice Sheet Instabilities

Kuala Lumpur, Malaysia
21–24 June 2010

Workshop Report

Edited by:
Thomas Stocker, Qin Dahe, Gian-Kasper Plattner,
Melinda Tignor, Simon Allen, Pauline Midgley

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IPCC Workshop on Sea Level Rise and Ice Sheet Instabilities

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Preface

Sea level rise is one of the major long-term consequences of human-induced climate change. Future projections of sea level changes and their regional expression are of crucial importance for the sustainability of coastal settlements around the world. The Fourth Assessment Report of IPCC (AR4) had comprehensively assessed key processes contributing to past, present and future sea level changes. However, process understanding was limited and thus both size and uncertainties associated with some of these contributions remained still largely unknown. This also hampered the overall projections of global mean sea level rise in AR4. The future dynamical behaviour of the large polar ice sheets of Antarctica and Greenland in a changing climate was identified as the primary origin of the large uncertainty in the AR4 projections of sea level rise for the 21st century.

IPCC Working Group I (WGI) has acknowledged the relevance of this specific topic and thus (1) proposed a chapter on 'Sea Level Change' in its contribution to the IPCC Fifth Assessment Report (AR5) and (2) organized a targeted IPCC Workshop on 'Sea Level Rise and Ice Sheet Instabilities' very early in the assessment cycle for the IPCC's AR5. This Workshop took place in Kuala Lumpur, Malaysia, from 21 to 24 June, 2010.

The Workshop brought together experts from very diverse disciplines with a wide range of expertise, covering oceanography, ice sheet dynamics, glacier research and hydrology to discuss latest results from both observations and modelling relevant for sea level change. The workshop structure included a combination of plenary sessions with invited keynote presentations, group discussions, poster sessions and, finally, topical breakout groups.

This Workshop Report contains a concise summary of the overall discussions and conclusions of the Workshop as well as summaries of the discussions in the breakout groups. It further includes the extended abstracts of the keynote presentations and poster abstracts presented during the Workshop.

A total of 93 invited experts from 38 countries attended the Workshop. We sincerely thank all the participants who contributed to a very constructive and fruitful meeting. The exchange of views and knowledge resulted in more clarity on the issues involved and the current status of scientific understanding. The excellent and efficient work of the Technical Support Unit of WGI at all stages of the Workshop organisation and production of this report is much appreciated.

We thank Prof. Fredolin Tangang, WGI Vice-Chair, for providing local organisational support, as well as the National University of Malaysia and the Malaysian Ministry of Natural Resources and Environment for their assistance with the excellent local arrangements and hospitality which contributed to the success of the meeting. The financial support of the IPCC Trust Fund and of the Swiss Federal Office for the Environment is gratefully acknowledged. We very much appreciate the advice of the members of the Scientific Steering Committee who shaped the Workshop programme and thank them for their help in carrying it out.

In summary, this was a very successful and stimulating meeting that brought together key communities to discuss topics relevant for a better understanding of sea level changes. We are convinced that this will be of great value in the preparation of the AR5 and hope that the product of this Workshop will provide useful information to the scientific community, in particular to many AR5 Lead Authors in several chapters of WGI AR5 that address the topics of sea level rise and ice sheet instabilities.

Thomas Stocker

Prof. Thomas Stocker
Co-Chair, WGI

Qin Dahe

Prof. Qin Dahe
Co-Chair, WGI

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Thomas Stocker, Co-Chair, IPCC Working Group I
Gian-Kasper Plattner, Science Director, IPCC Working Group I

Purpose of the Workshop

This Intergovernmental Panel on Climate Change (IPCC) Workshop, organized by Working Group I (WGI), addressed a topic of key importance for the WGI contribution to the IPCC Fifth Assessment Report (AR5). Sea level rise is one of the longest-term consequences of continued increase in anthropogenic greenhouse gases and threatens the livelihood of millions of people. While the physical processes that influence sea level changes are well known and established, the uncertainties in the projections of some of the components contributing to sea level rise are still unacceptably high. The largest uncertainty is associated with the response of the large ice sheets in Greenland and Antarctica, and their sensitivity to atmospheric and oceanic warming and changes in precipitation. For these reasons, the IPCC Plenary approved the proposal of WGI to hold an IPCC Workshop very early in the AR5 cycle so that the scientific progress since the last IPCC assessment (IPCC AR4, 2007) could be highlighted for a wider audience and areas of emerging results or major remaining questions could be discussed. The experts attending the Workshop covered a wide range of specialties including in situ and remote sensing observations of ice sheet movement and mass balance, reconstructions and direct observations of past and present sea level changes on regional to global scales, changes in ocean properties and circulation, glacier mass balance and dynamics, simulation of ice sheets and short and long-term climate projections. As sea level change is a truly cross-cutting issue, this workshop offered the opportunity to bring together scientists from research communities that normally tend to interact comparatively little.

Synthesis and Emerging Topics

There has been notable scientific progress since the Fourth Assessment Report (AR4) in the ability to estimate changes in the surface mass balance of the two major ice sheets of Greenland and Antarctica by a number of independent techniques. Gravity measurements and laser altimetry from satellites now provide information on mass changes and surface elevation changes, as well as changes in the velocity of rapidly flowing ice streams. While it has now been established that the current mass balance is negative for both large ice sheets, and their contributions to past sea level rise can be quantified, the uncertainties in the absolute numbers are still large and may amount to up to 100% for individual contributions such as those from ice streams or subsurface melting. Intercomparison projects for surface mass balance estimates were discussed at the Workshop and their importance was noted.

A critical limitation for the modelling of present and future evolutions of the polar ice sheets is the absence of detailed information on fjord bathymetry, bed topography and structure, as well as conditions of the adjacent ocean, in particular temperature, density structure and circulation patterns. Such information is required to estimate the dynamical behaviour of ice sheets at their margins and the propagation of perturbations generated at the margins towards the interior of the ice sheets. Stability properties of such systems are therefore difficult to estimate.

Various processes that could generate ice sheet instabilities were discussed by the Workshop participants and a ranking of their relative importance was presented. The marine ice sheet instability seems to be the most important and currently best studied process. This instability is caused by over-deepening of the underlying bed which explains the importance of detailed and high-resolution information on bed topography. The physical understanding of such instabilities in a 2-dimensional framework is well established, but it is not clear how this translates into a realistic, 3-dimensional configuration. Both stabilizing and destabilizing processes will be added in 3-dimensional setups potentially resulting in substantially different dynamical behaviour from that simulated by simplified models. Meltwater lubrication is also a widely discussed instability mechanism, but it now appears that its current importance is minor. With the expected expansion of surface melting, however, this situation may change in the future.

Glaciers and ice caps also contribute substantially to sea level rise. Current annual glacier and ice cap contributions are estimated to roughly equal those from the two major ice sheets in Greenland and Antarctica. However, while there has been some progress in the understanding of past and present rates of change in glaciers and ice caps, the uncertainties regarding the overall ice volume are still large, also hampering future projections of sea level rise. Improved data from the largest glaciers and ice caps are critically needed and some progress has been reported on estimates of ice thickness and glacier outlines for certain regions. In addition, a more mechanistic understanding of glacier dynamics (e.g., calving fluxes), and improved modelling of debris covered and polythermal/cold glaciers are required in order to project the magnitude and timing of the glacier and ice cap contributions to sea level rise into the future, in particular over the next few decades.

Ocean warming and associated thermal expansion is another major component of sea level rise. The coverage of upper-ocean observations has significantly improved through the world-wide use of XBTs (Expendable Bathythermographs) and the ARGO[1] programme. However, it has been found that corrections of systematic biases are necessary. A further limitation is the depth range of these floats which provide access only to about 2 km depth. In consequence, estimates of deep ocean heat content, relevant for the long-term evolution of sea level rise, are associated with large uncertainties.

The simulation of current and future sea level rise on regional to global scales requires the combination of the different components that contribute to sea level rise and their uncertainties, using comprehensive models. Comprehensive climate models still do not routinely include large ice sheets or glaciers and ice caps, thus limiting their use for both global and regional projections of sea level rise. The coupling of ice sheet/bed and ice sheet/ocean, for example, poses specific challenges which are only starting to be addressed. A complementary approach to the comprehensive modelling of sea level rise may be the determination of lower and upper limits of sea level rise through process-based models. These models would provide information of what is physically unavoidable and what is physically possible under extreme scenarios. In this regard, information from palaeoclimate records is very useful. Recent reconstructions of sea level rise from the end of the last ice age suggest that maximum rates of 20 to 50 mm/yr were realized at times of maximum meltwater discharge. However, these process-based models, in contrast to the comprehensive climate models, would not provide any information on the regional patterns and variability of sea level changes, information that is highly relevant for impacts studies.

Recently, various attempts using semi-empirical models have been proposed to estimate globally averaged sea level rise for the 21st century. No physically-based information is contained in such models and assumptions are based on relatively short and limited observational data. The assumption that the *rate of change of sea level rise* from those components that were small during the 20th century and which have been attributed to ice sheets would scale with *global temperature change* leads to a strong and unlimited amplification of future sea level rise when global temperatures continue to increase. Therefore, such approaches have generally yielded the largest sea level rise estimates for the end of the 21st century. A major limitation is the fact that the calibration phase for these semi-empirical models does not cover the range of climate-system behaviour that might be expected for the 21st century, i.e., significant loss of ice from the large polar ice sheets. The physical basis for the large estimates from these semi-empirical models is therefore currently lacking.

In conclusion, this IPCC Workshop has brought together the key communities that contribute knowledge, data, models, and understanding with a potential to determine the current sea level rise budget and estimates of future sea level rise. This has fostered the exchange between these communities at a very early stage of the AR5 cycle and hence affords the opportunity of accelerated progress in some crucial areas of this research field. Such progress is very welcome for the ongoing AR5 assessment by WGI, in which the topics of sea level rise and ice sheet instabilities are addressed in several chapters, including a separate chapter on Sea Level Change. This assessment may be supported by a sequence of more targeted research meetings whose planning is underway and will be under the auspices of the Task Group on Sea Level Variability and Change, which was established by the World Climate Research Programme (WCRP[2]) in 2009. In such meetings, future research needs to improve understanding and reduce uncertainties may also be discussed.

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[1] http://www.argo.ucsd.edu/

[2] http://www.wcrp-climate.org/

Breakout Group Reports

The Workshop included 7 topical breakout groups. The breakout group sessions provided an opportunity for participants to discuss in small groups some of the key issues related to Sea Level Rise and Ice Sheet Instabilities. Each of the breakout groups addressed topics of relevance to the IPCC Fifth Assessment Report (AR5), with a particular focus on how those could be assessed in the WGI contribution to the IPCC AR5. The Scientific Steering Committee for the Workshop prepared a set of questions in advance for each breakout group that were addressed by the experts. Each breakout group was lead by a team of a Chair and Rapporteur, who reported back to the Plenary the key conclusions from their breakout group. These key conclusions were then further discussed in the Plenary. Following the Workshop, the Chair and Rapporteur were tasked with providing summaries of the discussions to all the participants. Those summaries are given hereafter:

Breakout Group 1: Ice Sheets: Greenland - Observations and Projections of Changes

Chair: Waleed Abdalati, University of Colorado, USA
Rapporteur: Andreas Vieli, University of Durham, United Kingdom

Framing Statement

Breakout Group 1 focused on identifying key issues related to our understanding of the current ice sheet contributions to sea level rise, and factors that determine how well future contributions can be quantified. We focused on six questions, which are provided below along with the group's responses to these questions. In some cases, these responses directly answer the questions, while in many others, they characterize what we need to know in order to be able to answer more accurately those questions.

1. How well do we know the current Greenland mass balance and its spatial variability, and what is needed to reduce the uncertainty?

Estimates of the current state of mass balance have only been possible in the last decade with the advent of various satellite and airborne remote sensing techniques. As a result, the AR5 will include significantly improved estimates of ice sheet contributions to sea level as compared to the AR4. Every method, however, relies on different models and assumptions that lead to differences among the various techniques on the order of 50 Gt or more, part of which can be attributed to different time periods analyzed. In the last two years, these estimates are converging, but differences still remain. In order to reduce uncertainty, it will be necessary to perform intercomparisons using the various techniques over a common time period at the maximum spatial resolution that is appropriate for each technique. The differences between the estimates will provide important insights into the processes at work, the strengths and limitations of different techniques and the models that are a necessary complement to the observations on which these estimate are based.

2. What are the key uncertainties in predicting Greenland's contribution to sea level by 2100 for a given regional warming (e.g., 3°C), and over what time periods could extrapolation of the current rate of mass change be a useful tool?

The key uncertainties are ice dynamics, which can lead to potentially rapid changes, and surface mass balance, which will likely cause more slowly varying changes. Although models perform reasonably well in simulating recent and current surface mass balance, there remain significant differences, both in their total surface mass balance estimates (by more than 20%), and much more substantially among the individual components of surface mass balance (by as much as 100%). Specifically, key uncertainties and needs in surface mass balance modelling are: refreezing, which could be improved by insertion of detailed snowpack models; use of energy budget-derived melting (instead of positive degree day approaches), which depend critically on accurate evolving albedo and cloud radiation modelling; blowing snow sublimation, which a majority of models ignore; and precipitation rate and its sensitivity to model spatial resolution. A comparison project in the UK entitled GRIMICE[3] (The Greenland Ice Sheet Model Intercomparison Exercise) is under way to characterize the differences among the models that takes advantage of the recent release of a consistent high quality re-analysis data set for the last ~50 years: ERA40[4]. As these efforts move forward and as further comparisons between surface mass balance models and observations are made, the models can be refined and their accuracy improved. Despite the current lack of any formal efforts to take these steps, both are likely to be done by the scientists working in these areas in time for the AR5.

The dynamic response to warming, however, remains a very large uncertainty, which currently can not be conclusively taken into account in the models. This is a result of the lack of adequate representation of ice/ocean coupling, ocean forcing and outlet glacier geometry. Some of this is related to limitations in understanding of the basic physics involved, and some of this is a result of the lack of detailed knowledge of ice bed topography, ice thickness, bathymetry in the fjords into which floating ice tongues extend, and ocean properties. One important advance since AR4 is the understanding that the effects of basal lubrication and associated summer acceleration are of considerably less consequence than the processes at the ice/ocean interface. These effects are not negligible, and meltwater penetration can significantly alter the englacial thermal structure, but their potential effects are now thought not to be as large a driver as was assessed at the time of AR4.

Because the forcing of rapid dynamic changes at the margins is not well understood, and because, as has been learned since the AR4, the timescales of response and adjustment are extremely short (i.e., years), the value and validity of extrapolating recent mass balance beyond several years is very questionable. The transition of glaciers in southeast Greenland from accelerating mass loss to stable or decelerating mass loss suggests that dynamic loss processes probably have upper limits and slow down as they adjust to their new configurations and boundary conditions. Surface balance processes change more slowly than dynamic processes, and thus reduce the errors that may be associated with near-term extrapolation, but the dynamic component renders extrapolation very risky. Equally as important is the fact that there is no reason to believe in stationarity in the system. Thus any extrapolation must be rooted in an understanding of the ice physics and some insight into the variability of the system. Despite the likely nonstationarity of the system, records from the past, in particular over the last century, will be extremely valuable in putting today's changes into their appropriate context, and provide insights into the ways and rates at which the ice sheet can change.

Finally, it is important going forward to consider additional time scales on the order of 50 and 200 years, which are also of great societal interest. The half-century time scale is important because the migration or substantial modification of coastal infrastructure is a process occurring over several decades. The two century time scale is important because the magnitude of the investment needed to adapt to significant sea level rise is so large that planning horizons should extend well beyond this century.

3. What parameters and processes need to be known for the theoretical understanding of the calving and basal melting at marine margins and how well can we predict ice-ocean interface response in a warming climate?

There is a strong need for detailed bathymetry of glacial fjords and floating ice thickness to understand how these fjords are thermodynamically connected to the outer ocean and structurally connected with the adjacent ocean. Thus temperature and salinity data is needed to test models. In principle, basal melting of floating ice can be reasonably well modelled, but modelled coupling between the ocean system and the ice system is lacking. Such knowledge requires oceanographic and geometric knowledge, which includes information on the distribution of heat content and circulation beneath and around the floating ice. Both of these are strongly linked to bathymetry and ice thickness. Calving in response to oceanic and atmospheric forcings acts as a feedback. The strength of that feedback is not yet clear and much development is needed in the understanding of the calving process and in particular in its inclusion into ice sheet models.

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[3] http://www.cesm.ucar.edu/events/ws.2009/Presentations/Tarn/LandIce/bamber.pdf

[4] http://www.ecmwf.int/research/era/do/get/era-40

4. What are the key parameters, improvements in process understanding and modelling schemes needed to include ice stream dynamics in predictive ice sheet models for climate scenarios? Are we expecting a several fold change in ice velocity of outlet glaciers in a warming climate?

The key parameters needed are basal topography beneath grounded ice and information on the ice/ocean interactions as described in item 3 above. Basal topography is a critical element for determining the potential instability of outlet glaciers, as the sign and magnitude of the bottom slope determines the extent to which a glacier can retreat from marine forcings, and the rate at which such retreat can occur. Related is the need for higher spatial resolution ice sheet models in order to resolve the narrow ocean terminating outlet glaciers.

We do not expect a several fold change in ice velocity of the outlet glaciers that have already shown dramatic acceleration in any sustained manner. The levelling off in 2009 of glaciers in Southeast Greenland suggests – and theory supports – that there are some upper limits as to how sustained acceleration can be with time. It is more likely, as indicated by remote sensing data, for new areas to speed up, and for enhanced losses to move northward.

5. How important is understanding deep ice sheet flow properties for modelling current and future ice loss?

Understanding deep ice sheet flow properties is not very important on the decadal to century time scale, as the time scales of processes that affect non-sliding flow are much longer than this. Of much greater concern are the basal topography of ice streams and outlet glaciers and their ice/ocean interactions.

6. What can we say about the next 1000 years for the ice sheet?

This depends heavily on the temperature changes and climate scenarios expected in this time frame. We can safely say that the ice will shrink, but how fast will depend on the degree of warming. Current models that examine these changes are driven by surface mass balance, and the role of dynamics in long-term ice sheet decay is not fully considered. Over longer time scales surface melt will most likely become the dominant process of mass loss as the ice sheet and more specifically the majority of marine outlet glaciers will eventually lose contact to the ocean. The point by which this will happen is crucial but strongly depends on the scenarios of future warming.

Summary

The discussions in the breakout groups reinforced much of what has been learned since the AR4. Dynamics remain a critical uncertainty in the future of the ice sheet in the coming century. We have seen increasing evidence and more detailed records of this since the AR4, and have made clear progress in our understanding of the processes that control dynamics – e.g., the importance of ocean forcing, the timescales involved and the inland propagation of changes. Datasets of detailed basal topography of outlet glaciers and their downstream fjords now are slowly becoming available (as a result of NASA's IceBridge[5] effort among others, but large data gaps still remain. Further observations/monitoring of dynamics are important and need to be integrated into ice flow models. There has been considerable progress since the AR4 in process understanding and model development, which we expect will successfully inform the AR5, but many questions remain open, and the time it takes to incorporate what has been learned, even crudely, into ice sheet models is substantial. Thus some important gaps will likely remain for the AR5.

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[5] http://www.espo.nasa.gov/oib/

Breakout Group 2: Ice Sheets: Antarctica - Observations and Projections of Changes

Chair: Bob Bindschadler, NASA, USA
Rapporteur: Andrew Shepherd, University of Leeds, United Kingdom

Framing Statement

The future Antarctic contribution to sea level rise is likely to be complex to determine. The mass balance of the grounded ice sheet will vary regionally, changes in ice mass will be driven by changing precipitation, changing ocean temperature and circulation; potentially through ongoing responses to natural climate change in the distant past; and in a few regions, by changing atmospheric temperature. The possibility of magnified dynamic responses in the grounded ice resulting from the removal of ice shelves is also widely-discussed. Six questions were addressed in this breakout group. A summary of the discussion follows each question.

1. To what accuracy do we know the current rate that the Antarctic ice sheet is losing mass and contributing to sea level rise? How can we reduce the uncertainty? Does the current set of committed satellite missions represent a sufficient monitoring capability?

Three independent methods have been applied to determine the mass balance of the Antarctic ice sheet: 1) mass change from GRACE[6] (Gravity Recovery And Climate Experiment); 2) elevation change from radar and laser altimetry; and 3) volume flux from InSAR[7] (Interferometric Synthetic Aperture Radar) and meteorological models). The aggregate view arising from numerous applications of these methods has revealed a pattern of increasingly negative mass balance (as in Greenland), but each method has weaknesses and intercomparisons suggest that errors of individual analyses may be underestimated. The breakout group recommends that a careful intercomparison of the analyses from each method for comparable spatial and temporal domains be conducted to strengthen each of the analyses and produce a consistent set of mass balance results with smaller uncertainties. Reduced errors would also improve the uncertainties in projections of future mass balance based on extrapolations from the observational period.

Ancillary data, specifically ice thickness and bedrock elevation especially in coastal areas, Glacial Isostatic Adjustment (GIA) in areas experiencing rapid uplift, and surface mass balance observations in the broad regions presently devoid of surface meteorological data, would make significant improvements to knowledge of current mass balance. An additional key diagnostic of change would be grounding line migration, presently unavailable from current satellite sensors. The European Space Agency (ESA[8]) is considering moving ERS2[9] into a 3-day repeat orbit which would allow the first measurement of many grounding line positions since the late 1990's.

The record of the past 200 years of Antarctic climate collected by the International Trans Antarctic Scientific Expedition (ITASE[10]) programme should be able to assist in quantifying the temporal variability of the surface mass balance. 'Accumulation radar' data proved extremely useful in addressing this same issue and the introduction of an airborne accumulation radar could rapidly expand the spatial extent of these data.

Satellite-based observations have been crucial, but few of the most important sensors continue to operate. CRYOSat-2[11] is new but could bridge the gap created when ICESat[12] elevation data collection ended in 2009. There is currently no InSAR capability to monitor ice velocity and grounding line dynamics (see note on ESA above) and a GRACE follow-on mission is still unfunded. Thus, at precisely the time when satellite data could prove most useful for observing the pace of ice sheet change, the suite of existing and committed satellite sensors is limited.

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[6] http://www.csr.utexas.edu/grace/

[7] http://solidearth.jpl.nasa.gov/insar/

[8] http://www.esa.int/esaCP/index.html

[9] http://earth.esa.int/ers/

[10] http://www2.umaine.edu/USITASE/

[11] http://www.esa.int/esaMI/Cryosat/index.html

[12] http://icesat.gsfc.nasa.gov/

2. What are the key uncertainties in predicting the change in mass of the Antarctic ice sheet over the 100-year timescale? Over what time period could an extrapolation of the current rate of mass change (if it were precisely known) be a useful tool for projection of decadal to century change?

In terms of the ability to predict the future of the ice sheet, the primary obstacle is the poor understanding of critical processes that are causing current changes, primarily the nature of ocean-ice interaction and the ice sheet response to grounding line retreat. Knowledge of coastal bed geometry and bathymetry were identified as significant gaps. Scenarios for estimating upper/lower confidence limits of future ice mass loss may be more useful than best-estimate projections, which are likely to be tricky. Progress in this area is likely to be slow as it requires considerable field work and sustained data collection, much of which has either not yet begun or is in a very early stage.

In light of the rather immature state of predictive capability, extrapolation was discussed at some length. A general sense emerged that extrapolation should not extend over a time interval greater than the time interval of observations being extrapolated. Extrapolations of linear trends have more confidence than extrapolations of higher order fits, but no additional guidance was agreed on. It was apparent that extrapolations would be improved by reducing the uncertainty of the base observations, thus, the breakout group recommendation that the multiple estimates of current mass balance be reconciled to an optimum collective.

3. Is the thinning or loss of ice shelves likely to have an imminent or long-term impact on the mass-balance of the Antarctic ice sheet? What improvements need to be made to ice sheet dynamical models in order to predict the response?

It was universally acknowledged that ice shelves are a crucial element in the dynamic contribution to present and future ice sheet mass balance. That said, there are large voids in understanding the processes of ocean-ice shelf interaction and the nature of the basal traction inland of the grounding line, as illustrated by the divergent responses of Pine Island Glacier which is retreating and accelerating in response to ice shelf thinning, and Thwaites Glaciers which is maintaining its speed while widening. There is an expectation that the bulk of the work necessary for improving the treatment of ocean-ice interaction lies within the oceanographic community, through the development of ocean circulation treatments for the continental shelf areas to capture the introduction of Circumpolar Deepwater from the deep ocean onto the shelf, and follow its motion once there. It was suggested that oceanographers may not find this problem sufficiently exciting to put much effort into solving it. An even broader view was offered that connections must also be built between the larger, more distant climate components and the ice shelves.

4. The recent strengthening of the westerly winds around Antarctica apparently had major impacts on near coastal water temperatures along the Antarctic Peninsula. What are the predictive capabilities of ocean temperature and circulation in a warming climate and how would they impact ice shelf stabilities and ice flow rates?

Pathways for such teleconnections are not well known and there is a low expectation that these links will be addressed in the short term despite the fact that Atmosphere-Ocean General Circulation Models (AOGCMs) are known to perform poorly in key regions for the ice sheet, e.g., Amundsen Sea. Some participants noted that effort in the AOGCM community is directed more to simulate climate scenarios for the AR5 and not to improve ice sheet coupling or skill of models regarding ice sheets. Ice2Sea[13] was mentioned specifically as the only known integrated effort to couple the AR5 scenarios to ice sheet evolution.

5. Estimates of surface mass balance in Antarctica are poorly constrained; how can we reduce the uncertainty in accumulation rates and the predictive capability in a warming climate?

Recently reported work casts doubt on the ability of surface mass balance models to adequately account for mass loss by blowing snow along much of the Antarctic coasts, but the dearth of data in the interior leaves uncertain the veracity of these models over much of the continent. Agreement with data has limited impact when the validating data are

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[13] http://www.ice2sea.eu/

extremely sparse or were used in assimilation schemes and, thus, indirectly introduced into the model. The acknowledged need for well distributed observations of precipitation, water vapour and wind to improve this situation is unlikely to improve in the short term. An alternate view was offered that ice dynamic changes will dominate future significant Antarctic contributions to sea level, relegating surface mass balance changes to a relatively minor role. Countering this dismissive view was the recognition that an incorrect surface mass balance leads to errors in AOGCMs through the temperature and water vapour fields, and that without better validation data, the surface mass balance models will not be improved and that surface mass balance rates are often 100 times larger within the all-important coastal regions as compared with the drier interior.

6. What can we say about the next 1000 years for the ice sheet?

In a very real sense, projections on the 1000-year timescale are likely to be more tractable than the 100-year timescale. In a general sense, the Antarctic ice sheet will likely be smaller with losses concentrated in the areas of fastest outflow. Central East Antarctica might grow, but more than compensated by loss at the margins. West Antarctica will lose more mass than East Antarctica. Peninsula shelves will continue to erode/disintegrate with a corresponding loss of mass from Peninsula glaciers. The stated interest in the 1000-year timescale might be a legacy from earlier IPCC reports when it was not thought the ice sheets could change markedly on a centennial timescale. Nevertheless, the millennial timescale is relevant to the mitigative policy deliberations, including ethical considerations.

Breakout Group 3: Glaciers and Ice Caps: Observations and Projections of Changes

Chair: Georg Kaser, University of Innsbruck, Austria
Rapporteur: Jon-Ove Hagen, University of Oslo, Norway

Framing Statement

Glaciers and ice caps currently store ~0.5 m of sea level equivalent, and their current mass loss contributes ~1 mm/yr to sea level rise (about 400 Gt/yr). This is approximately equal to the combined contributions from ice sheets in both Greenland and Antarctica. Glaciers added significantly to global sea level rise in the 20th century, and will continue to contribute into the 21st century and beyond. Although this source of sea level rise will ultimately decline (once the glacier reservoir is depleted) there is no clear understanding of the future evolution of glacier and ice cap melting.

In this breakout group, we addressed past and future changes in glaciers and ice caps. Glaciers and ice caps have previously been defined (in AR4 and earlier reports) as including those glaciers and ice caps surrounding the two ice sheets of Greenland and Antarctica. This definition should remain in place for the AR5, in order to avoid any confusion. We have addressed the following questions:

1. What assessments of global glacier volume and of its changes in recent decades are available? How uncertain are they? Are monitored glaciers representative of the total glacier mass balance? What is the level of the associated uncertainty (for the past and future)?

A complete inventory of the Earth's glaciers does not yet exist. Estimates of the overall ice volume of glaciers and ice caps therefore contain large uncertainties. Yet, improved extrapolation and scaling efforts have constrained the total mass in glaciers and ice caps to be slightly above 0.5 m sea level equivalent. Our current understanding of the recent past and the actual rates of changes have improved since the AR4, and are within acceptable ranges of uncertainty. However, uncertainties are still quite large for the future. The spatial distribution of existing glacier mass balance monitoring is not representative of the global glacier coverage contributing to sea level rise. There is an urgent need for improved data from the largest glaciers and ice caps. Further monitoring of mass balance is also required in poorly sampled climatic regions, as is homogenization and quality control of existing mass balance series.

2. Can we obtain a best estimate and uncertainty for glacier and ice cap contribution to sea level in various periods e.g., 1960-present or 2000-present? Should we include hypsometric feedback on mass balance sensitivity?

It is feasible in the AR5 to come up with more detailed and complete area and volume inventories, and related changes for selected regions. New global digital elevation models, ice thicknesses and glacier outlines will improve our ability to carry out sensitivity studies, assessments and projections. New hypsometric information might also improve our understanding of the time scales characterizing current glacier response.

3. What is the relationship between recent glacier change and recent climate change, globally and locally? How should we make projections of changes in global glacier mass balance on the basis of AOGCM climate change projections?

Regional climate variability has the potential to strongly influence the behaviour of glaciers. For example, some glaciers in Norway and New Zealand have advanced in recent decades in response to changes in atmospheric circulation. We are now in the position to address the attribution of observed changes in greater detail. Considering the problem of local variability requires the development of downscaling techniques from AOGCMs to glacier scale, and/or the use of regional atmospheric models. Both approaches are in progress, but these may not yet be available for comprehensive assessments such as AR5.

4. How should we project glacier area and volume change from mass balance changes? Is it acceptable to use volume-area scaling?

Volume-area scaling is a physically sound and useful tool for estimating total glacier and ice cap volume and change, and for respective spatial extrapolations. However, improvements are needed. This is now possible because we have a larger number of ice thickness estimates available. A greater effort is needed for physical (flow line) modelling of the contribution from glaciers and ice caps to sea level rise.

5. Is rapid dynamical change in glaciers an important issue and if so how should it be dealt with?

There is a considerable potential for glaciers and ice caps to exhibit enhanced dynamic responses and corresponding accelerated mass loss for those glaciers which interact with the ocean. The fraction of mass loss that occurs through iceberg calving appears to be as much as 30-40% in regions where it has been observed, but it has not been measured over large areas. Uncertainty in estimating calving fluxes is therefore adversely affecting our ability to predict current and future rates of mass loss from glaciers and ice caps. We also lack an adequate understanding of debris-covered and polythermal/cold glaciers. Improved models of these glaciers are needed. Despite these unknowns, the uncertainty in sea level predictions will remain dominated by the ice sheet dynamics term. Uncertainty from the glaciers and ice caps is far smaller.

6. What is happening to glaciers on Greenland and Antarctica and nearby islands and are there any specific concerns over their future behaviour?

The glaciers in Greenland and Antarctica and the nearby islands will respond quickly and contribute significantly to sea level rise, but their behaviour is different to that of the ice sheets. The use of gravity anomalies as provided by spatially coarse data from GRACE is a powerful tool for detecting ice mass changes. However, it requires an improved determination of the mass changes of glaciers and ice caps surrounding Antarctica and Greenland. Improved glacier inventories in these regions, and numerical modelling of important glaciers and ice caps in Greenland and Antarctica will advance our understanding of processes in these key regions. It will also allow us to reduce uncertainty in GRACE estimates by distinguishing between the ice sheet and glacier signal, in order to avoid double counting these changes.

Breakout Group 4: Thermal Expansion and Halosteric Effects

Chair: Susan Wijffels, CSIRO, Australia
Rapporteur: Syd Levitus, NOAA, USA; Susan Wijffels, CISRO, Australia; Felix Landerer, California Institute of Technology, USA

Framing Statement

In the 20th century ocean warming and its associated thermal expansion accounted for 30-50% of observed sea level rise. Due to their huge thermal inertia, the oceans will continue to warm and expand for decades even if greenhouse gas concentrations are to be stabilised. Ocean circulation changes dominate regional sea level patterns, with natural modes of variability such as ENSO (El Niño-Southern Oscillation) or the North Atlantic Oscillation combining with multidecadal changes to impact on extremes. Halosteric effects also become important. Recent data point to widespread abyssal warming becoming a significant contributor to thermosteric sea level changes both regionally and globally.

The Observational Record:

1. What is the uncertainty of estimates of the contribution to global mean sea level change from thermal expansion from the instrumental record, over the last several decades, and during recent years?

Individual studies of the thermosteric component of sea level change have all included confidence intervals. Generally the confidence intervals decrease with time as more data have become available. Studies have been published comparing different estimates of the thermosteric component, e.g., Levitus et al., 2009; Lyman et al., 2010; Palmer et al., 2009. Substantial differences exist between different thermosteric component estimates, some of which derive from differences in how data biases are applied. One international workshop has been held on biases in XBT measurements and another meeting was held in August 2010. Biases in profiling floats have been quickly identified by the ARGO community and the research community has been informed. Corrections to these profiling float data will be made in delayed mode by the relevant data assembly centres by the end of 2010. To have a climate observing system there must be continuous monitoring of data for quality and biases. This must include data reporting and management which can also introduce errors into the system. An example of this is the misreporting of temperature profiles as being made by an XBT instrument when in fact the measurements were made by a CTD (Conductivity, Temperature, and Depth) instrument.

2. What has been the past rate and regional pattern of steric sea level rise (thermosteric and halosteric)?

Multiple estimates of the past rate and regional patterns of sea level change of the thermosteric component have been made. However some regions such as the Southern Hemisphere have not been well-sampled in the past. Another poorly sampled region is the western Indian Ocean. Also, the deep ocean is still not well sampled because ARGO floats only extend to approximately 2000 m depth. The point arose as to whether monitoring the areal extent of polynias around Antarctica might provide an estimate in the formation rate of Antarctic Bottom Water. Changes in bottom water properties are documented but historical data are scarce.

3. What data biases remain and how much uncertainty do they introduce into existing estimates of rates and pattern of change? Can we quantify the contribution from the deep ocean to thermal expansion (last 50 years + ARGO era)?

Biases remain in XBT data and different techniques are used to minimize these biases. This can lead to differences in estimates of the thermosteric component. Some profiling floats also contain biases. Some of these biases can be reduced but in some cases data must be eliminated from use. Lack of data in some areas may cause spatial biases. This includes ice-covered regions, deep water, and the western Indian Ocean (due to pirate activities). Modern day evidence for changes in the temperature and salinity properties of bottom water exists but historical data may not be precise enough for such studies. The North Atlantic is well-covered with historical and modern temperature and salinity data and multiple studies have documented changes in North Atlantic Deep Water that have caused changes in thermal expansion and haline contraction.

Simulations of the 20th Century:

1. How well do GCMs simulate 20th century changes and patterns? Can they help with supplementing observations?

2. Following recent work on instrumental corrections, is there now satisfactory agreement between AOGCM simulations and observational estimates, regarding both the trend and the magnitude of interannual variability? If not, what is the best way to use AOGCM results to make projections?

Global average sea level rise appears to be well simulated by CMIP3[14] models with full aerosol effects (although the ensemble has a slight cool bias). However, modelled regional patterns of sea level trends are very divergent. A fundamental question is whether the large spread among the regional patterns of AOGCM is dominated by natural variability (of the 50-year trends) or differences in model physics, or forcing differences. With better observations of regional patterns (thermosteric/halosteric), there is an opportunity to use long control runs and examine the statistics of the 50-year trends in steric patterns to see whether the 20th century forced changes are detectable in the models and then in the observations. We can view the new observational patterns as an opportunity to see if more formal attribution is possible. Models will also give us a clearer view of the significance of observed sea level patterns and the impact of natural regional variability. The dynamics of regional response have not been diagnosed except for some regions and for some models. The physics of multidecadal changes is not well understood in most systems – long model runs provide an opportunity to explore these in a more consistent and multimodel approach, focusing on sea level impacts. The veracity of how well models capture the natural modes remains a challenge – natural modes do impact regional sea level. While ENSO in models has been well studied, other natural modes have been less so. The impact of these natural modes on sea level is not well documented and could be advanced quickly using model data sets. This question can also be explored using the relatively new multidecadal ocean reanalysis products.

Model drift and its implications for modelled sea level rise are not well documented and may be hidden to users in the adaptation/projection community. Drift should be systematically documented for all runs and a means of removing it recommended to help isolate the forced signal.

How defendable is it to linearly 'remove' the drift from the control run? Ideally model sea level drift should be reduced in future modelling systems. To attribute changes more clearly, dedicated ensembles of model runs for the 20th century under isolated forcing (solar, volcanic aerosols, ozone, tropospheric aerosols, long-lived greenhouse gases) are required. If such runs already exist for CMIP3 models, modelling groups could do the community a great service by making these publically available as CMIP3 will be the basis for many papers in the AR5.

Deep ocean: Relatively few studies exist diagnosing deep ocean changes in multiple models. Partitioning of sea level rise between the upper and deep ocean in most models is not well documented. Now with the new observational estimates, we believe comparisons are worthwhile where patterns and rates of abyssal warming are explored. Models that closely reproduce observed patterns could give insight into the dynamics of the deep changes (too fast for ventilation) and help us do a better job of extrapolating sparse observations into a more accurate global integral. Again, model drift would have to be dealt with in these studies, and they might give insight into whether non-linear drift effects play a role on multidecadal timescales.

Projections:

1. How do we assess the systematic uncertainty in projections of global thermal expansion?

Ocean heat uptake in the models is sensitive to ocean mixing rates/subduction efficiency. A clear assessment of modelled simulated fluxes is needed. Inter-model spread is bigger than scenario spread for a single model in regional sea level rise patterns. This suggests that intermodal model circulation/process differences dominate the ensemble variance. More work is required to understand the ocean heat uptake efficiency in models and in the real ocean. It is not clear whether 'climate sensitivity' is a useful concept for the transient problem where ocean thermal inertia is one of the rate setters.

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[14] http://cmip-pcmdi.llnl.gov/

One way to narrow down projections is to derive model weights by using observations as model constraints. The IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections[15] held in January 2010 discussed these approaches (IPCC, 2010). This may provide guidance on how to approach sea level projections. But this approach requires good, reliable observations of thermosteric and halosteric changes. However, it was noted that when comparing models to observations during the 20th century, models can be right for the wrong reasons. Models need, among other things, natural and anthropogenic forcings (e.g., volcanic aerosols, solar variability, etc.)

2. Are trend patterns of projected regional sea level changes stationary in space? If so, could these be used to compare to the last 50 years and perhaps derive model weights?

For the AR5, modelling groups should report thermosteric/halosteric sea level contributions for different depth intervals (to allow for comparison to observations, e.g., 0-700 m) and quantify the control run drifts.

3. Do the models capture the natural 'modes of variability' and their impact on regional sea level extremes? Is there any skill in projections of how these modes will change?

The major global mode of sea level variability is ENSO. Some models simulate ENSO well, but many do not. There is no convergence in projections for ENSO 'trends', so no skill in predicting changes in interannual extremes will be possible. Other major regional modes such as the North Atlantic Oscillation or the Pacific Decadal Oscillation, are less well assessed across models, with little focus on their sea level impact. A comprehensive assessment across models would be helpful.

4. Why do AOGCMs not agree on the geographical distribution of future sea level change due to ocean circulation and density change? What should/can be done to improve this?

There is an increasing spread of regional sea level projections from the IPCC Third Assessment Report (TAR) to the AR4. It is possible that there will be an even larger spread in the AR5. Understanding and communicating the reasons for this will be important. The reasons for model spread is likely to be that the models do not simulate the mean large scale ocean circulation well, and hence the intermodal spread in the mean circulation fields maps into the changes. It would be useful to assess the pathways of ocean heat uptake across models, and wind changes. Projection spread may be reduced by considering deriving model weights (see above – this relies on good observations of past sea level patterns), but care must be exercised (see IPCC, 2010). Weightings could be based on evaluating individual model behaviour and identifying their skill in mechanisms/processes like the global Meridional Overturning Circulation, key currents, overflows and so forth.

Thermosteric versus halosteric patterns: is one more robust than the other, in both the observations and models? While model agreement is better for large scale warming, rates and patterns of fresh water flux change have much greater inter-model spread.

Detection/attribution of regional patterns of change have not yet been done for sea level. It is sensible to start on a basin scale and some researchers are already doing this. It would be valuable to evaluate AOGCMs projected trends versus the natural variability of regional sea level variations (e.g., based on the control simulations). This could be done across various spectral windows to look at the regional effects of different modes of variability. It is important to recognize that achieving reduced spread itself does not imply improved skill and is not a desirable goal on its own. To gain confidence, we need to understand the mechanisms driving patterns of change.

The relative value of decadal predictions versus projections was not discussed in this breakout group, but reserved for Breakout Group 6.

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[15] http://www.ipcc-wg1.unibe.ch/publications/supportingmaterial/IPCC_EM_MultiModelEvaluation_MeetingReport.pdf

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Breakout Group 5: Accounting for Past Sea Level Change

Chair: Philip Woodworth, National Oceanography Centre, United Kingdom
Rapporteur: Yusuke Yokoyama, University of Tokyo, Japan

Framing Statement

Understanding the past history of sea level change is the key to better prediction of its future. This breakout group discussed past sea level changes in several time slices, including past interglacials, past glacial maxima, interstadials, and deglaciations, historical time frame (last 2000 years) and instrumental era (20th century). Issues in postglacial rebound and past sea level indicators (dating, palaeo sea level indices etc.) have also been addressed.

1. What is the timing and nature of sea level rise during the course of deglaciations? What contribution, if any, to the current rate of global sea level rise comes from the ongoing response of large ice sheets to the end of the glacial period?

Sea level changes observed in different parts of the world have been neither identical nor 'eustatic'. The predominant effects of GIA, which results from changing surface loads, must be taken into account in the observations. Nonetheless, if there is a large amount of data, a good model of global sea level change during deglaciation can be constrained.

The accuracy of sea level observations has increased in recent years because of technical advances (e.g., chemical measurements) and greater sampling. Offshore ice age corals can now be be retrieved using the resources of international collaborative projects, e.g., IODP[16] (Integrated Ocean Drilling Program). Powerful mass spectrometers are available, and uncertainties for U-series dating on corals can now be achieved to better than the one part per thousand level of accuracy.

The last deglacial period started at about 19 kyr with an average rate of sea level rise of 10 mm/yr punctuated with several rapid rises at 19 kyr and 14 kyr of 20 and 50 mm/yr respectively (the latter being a 17 m in 350 yr lower bound on the most rapid rate of rise). These rapid rises occurred over bicentennial timescales. It remains to be seen whether studies of Melt Water Pulse 1a in particular, which occurred during the middle of a deglaciation, may be relevant or not with regard to ice sheet changes in the next century, considering that the Earth is now in an interglacial period.

The start of the last deglaciation coincided with the time when high latitude Northern Hemisphere summer insolation increased. This initiated the melting of both the Laurentide and Fennoscandian ice sheets and resulted in the first rapid rise of sea level at 19 kyr. Introduction of freshwater weakened North Atlantic Deep Water formation, and hence the Southern Ocean was warmed because of the mechanism called the 'North-South Thermal See-Saw'. Warming in Antarctica was recorded clearly in Antarctic ice cores, and that co-varied also with CO_2 as is also captured in the ice record. Increasing atmospheric pCO_2 induced more melting of the Northern Hemisphere ice sheets and this feedback continued until ~7 kyr. Ocean volumes approached their present day level but did not attain it precisely until 3-4 kyr. Therefore, sea-level rise during the last deglaciation was the consequence of interactions among the different systems of the earth surface including the cryosphere, ocean and atmosphere. Although there was a cold climate event between 11.6-12.8 kyr called the Younger Dryas, a sea-level reversal was not reported but a slow-down in the rate of rise (~8 mm/yr) was observed.

The picture for the penultimate deglaciation (Eemian) was not identical to the last one. Initiation of the ice melt occurred when the high latitude Southern Hemisphere insolation was high, and not the Northern Hemisphere insolation. It is also noteworthy that a large sea-level reversal took place during the Emian deglaciation, as was not seen in the last deglaciation. The rate of the reversal was as fast as 80 mm/yr and current ice sheet models cannot reproduce this fast growth. This provides a collaborative challenge for the modelling and data communities, but is strongly encouraged.

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[16] http://www.iodp.org/

As for the contribution to the current rate of global sea level rise from the ongoing response of large ice sheets, the breakout group did not discuss this apart from noting the ~0.1 mm/yr component discussed in the TAR.

2. What are the timing and magnitude of variations of global sea level during the last few millennia, before any anthropogenic influence? How unusual is the current rate of sea level rise (i.e., since 1900) compared to the last centuries?

We do not have input from instrumental measurements or even much palaeo-geological data during this period. However, the Mediterranean area possesses proxies which enable us to infer the sea levels of ~2k years ago and hence the changes since. For example, fish tanks found at numerous archaeological sites from the Roman period provide a good analogue for understanding sea level changes. The limitation of such data to the area surrounding the Mediterranean is a concern, given that estimates of sea level change are strongly influenced by which GIA adjustment model is used. Also, the Mediterranean as an almost closed basin may have special oceanographic properties. Nevertheless, the Mediterranean archaeology data (fish tanks) can be used to suggest no more than approximately 14 cm of 'eustatic' rise in the last 2000 years.

Observations from corals, saltmarshes etc. located outside the Mediterranean Sea and far away from the former ice sheet are urgently required. While uncertainties regarding GIA correction may limit determination of 'absolute' trends, changes of trend or 'accelerations' can often be identified, e.g., during the 19th century in the saltmarsh data sets of various groups. Evidence for accelerations also needs to be explored further back in time during the Medieval Warm Period.

Different types of proxy data during the last few millennia (as for the longer timescales addressed in the first question addressed by this breakout group) present their own problems with regard to both elevation measurement and timing. The sharing of these data sets among the communities is strongly encouraged as a means to validating existing ideas of sea level change. The PAGES[17] (Past Global Changes)/IMAGES[18] (International Marine Past Global Change Study) PALSEA[19] (PALeo-constraints on SEA-level rise) Working Group or other international consortia could be used to co-ordinate these actions; the consortia could assess the data to be listed and apply quality control.

3. What is the uncertainty of the estimates of global sea level rise during the 20th century from tide gauges, and more recently from altimetry? How can we reduce the uncertainty? For instance, how can we improve GIA models and estimates of GIA corrections to apply to tide gauges, satellite altimetry and GRACE space gravimetry data?

The 20th century trend from tide gauges (approximately 1.7 mm/yr) and that since the early 1990s from altimetry (over 3 mm/yr) each have an estimated accuracy of the order 0.4 mm/yr. Uncertainty in the former may be reduced potentially through GCM simulation studies of the effect of tide gauge sampling and of variable data quality with time (i.e., general tests of heterogeneity). It was noted that a considerable amount of data remains for data-rescue (including paper charts and tabulations), as recognized by the Global Sea Level Observing System (GLOSS[20]) programme, for example. Local datum control (levelling of benchmark networks), and GPS for vertical land movement and positioning of the tide gauge data in a geocentric reference frame, are essential.

It was noted that GIA models have indeed improved in recent years (e.g., through incorporation of rotational feedback). Developments under way include new ice histories and construction of 3D visco-eleastic models containing lateral inhomogeneities. In general, more geological observations of palaeo sea levels will lead to better GIA models as will geodetic (GPS and absolute gravity) observations of vertical land movement (particularly where limited geological information exists e.g., in Antarctica), especially when the palaeo observations extend the geological record back

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[17] http://www.pages-igbp.org/

[18] http://www.images-pages.org/

[19] http://eis.bris.ac.uk/~glyms/working_group.html

[20] http://www.gloss-sealevel.org/

towards the Last Glacial Maximum. Continued confrontation of GIA models with tide gauge sea level trends will also help resolve model inconsistencies.

4. How much of the variation in decadal-mean sea level rise during the instrumental record is due to the uncertainty of measurement rather than a true global signal?

It is quite possible that some of the decadal variability observed in 'global' average time series and reconstructions for the 20th century reflects some of the regional and local variability in the tide gauge records. Such sampling bias needs to be studied more with the use of AOGCM fields.

Particular examples of decadal-timescale variability include the accelerations seen in the 1920-1930s in reconstructions and in many individual tide gauge records, and decelerations post-1960, and the accelerations since the 1990s. However, corresponding changes are seen in land and marine temperature records and in many climate indices, so such decadal features in the global sea level record appear plausible.

5. How can we improve sea level budget estimates over the past 50 years and altimetry era? What can we say about the contribution from land water storage?

New budget estimates for the last 50 years and the recent decade (see Cazenave, 2010 and Church et al., 2010) indicate encouraging continued improvements in understanding of each component of the budget. Major concerns were expressed in the breakout group as to the lack of knowledge of anthropogenic land water wastage (e.g., water mining as agricultural needs have increased), compared to the relative understanding of anthropogenic land water storage in dams. It was noted that even a relatively well-understood component such as the glacier contribution for the 20th century had been revised by a factor of 2 in recent years and that it was not clear what its real uncertainty should now be estimated as (see Breakout Group 3). Budgets need to be studied further back than the 50 years stated in this question.

It was suggested that the availability of 7 years of GRACE data alongside modern hydrological information (good seasonal and inter-annual correspondence having been observed) could lead to more insight into 20th - 21st century change as a whole, although it was not immediately clear how that could be done. Compilations of all available hydrological measurements (e.g., dam, groundwater, etc.) need to be compiled.

6. Why are AOGCMs unable to reproduce the 20th century global mean sea level rise? Is that worrying for future projections?

This topic was also discussed in Breakout Group 4. AOGCMs can do a reasonable job in simulating time series of global upper-layer thermosteric change but are less good at providing regional patterns and time series of total water level. However, based on the CMIP3 model archive one can now do a better job for total water levels, but still not for the spatial patterns. Further understanding of the deep ocean steric component would provide one key to improvement.

7. How accurate are past (last 50 years or so) sea level reconstructions (2-D; based on different types of observations)? What can we learn about the dominant modes of (natural) regional sea level variability and associated time scales? Can ocean circulation models -with and without data assimilation - help? Do AOGCMs give realistic hindcasts of regional change?

The breakout group found it hard to suggest a particular accuracy, but it noted that, in one study at least, reconstructions using altimetry and AOGCM fields as basis functions did lead to significant differences in global means and regional distributions. Comparisons of the latter to maps of thermosteric change can provide a qualitative validation. More studies need to be made of sea level changes in marginal seas (e.g., Irish Sea, Yellow Sea). AOGCMs with data assimilation obtained in reanalysis efforts should provide more reliable spatial fields than those without assimilation.

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Breakout Group 6: Projections of Global and Regional Sea Level Change

Chair: Leonard Nurse, University of The West Indies, Barbados
Rapporteur: Malte Meinshausen, Potsdam Institute for Climate Impact Research, Germany

Framing Statement

This breakout group covered issues surrounding future sea level rise projections, with the exception of ice sheet dynamics, which were discussed in Breakout Group 7. The main task was to take stock of existing methods, tools and datasets - categorized by individual contributions to sea level rise. Their respective skill for projecting global mean sea level rise is diverse. An open question remains how future projections may account for a mismatch between the observations of the sea level rise budget and current modelling capabilities, if any. Potentially, kinematic constraints, semi-empirical approaches and other scaling approaches could inform estimates of projections, specifically upper bounds – although large uncertainties remain. The specific challenges for regional sea level rise were discussed. A methodological synthesis of different approaches to advance beyond the AR4 in order to capture multiple evidences for future sea level rise remains a challenge. Across all components, the most significant improvements in our scientific process understanding is likely to arise in the area of ice sheet dynamics, starting from very sparse understanding of observed dynamics during the AR4.

1. How should we make projections of the contributions to global sea level rise from thermal expansion, glaciers and the ice sheet surface mass balance? What are the particular systematic uncertainties in each of these terms, and for each of them, can we use observations to constrain the projections?

The starting point for the discussion has been to briefly review the approach taken in the AR4 to arrive at sea level rise projections for the 21st century. In particular, this approach took into account: 1) Surface Mass Balance of Greenland, West Antarctic, and East Antractic Ice Sheets - using a degree day / surface mass balance model (Huybrechts et al., 2004) fed with high-resolution GCM time-slices and scaled by CMIP3 GCMs; 2) Glaciers and small ice caps - using a global glacier mass balance sensitivity (mm/yr/degree) from global observations over the last 50 years with volume area scaling (van de Wal and Wild, 2001; Oerlemanns et al., 2005); 3) Steric effects - using GCMs for SRES A1B and scaling using results from the simple climate model 'MAGICC'; 4) Land storage - ignored; 5) Total sea level rise estimate - aggregated from components.

The group then took stock of existing models, approaches, recent observational and palaeoclimatic data that might assist the AR5 in building and going beyond the methodological approach taken in the AR4. While new a) GCM, high-complexity/physical process based model capability; b) kinematic constraints, empirical and semi-empirical approaches; as well as c) advanced observational datasets are available for use in the AR5, the group did not comprehensively collect a list of tools. The overarching question for the AR5 will be how best to combine these multiple lines of evidence for each or all of the sea level rise components. While current semi-empirical approaches fill for example the niche of making 'all-inclusive' global projections, other process-based models tackle individual sea level rise contributions with more or less process detail. One important issue in particular is regarding the gap between individual sea level rise budget terms derived by current modeling capabilities and observations. This gap was acknowledged in the AR4, but did not inform future projections. Concerning the ice sheets, a number of larger research programs in the European Union, USA and elsewhere are expected to provide substantial new information for the AR5, such as SeaRISE[21] (Sea Level Response to Ice Sheet Evolution), ice2sea[22] and COMBINE[23] (Comprehensive Modelling of the Earth System for Better Climate Prediction and Projection). Sediment drilling projects such as ANDRILL[24] (Antarctic Geological Drilling Research Project) might provide additional constraints on total mass balances, and other projects are under way attempting to constrain specifically the accumulation rates over ice sheets, such as ITASE.

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[21] http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment

[22] http://www.ice2sea.eu/

[23] http://www.combine-project.eu/

[24] http://www.andrill.org/

For glaciers and ice caps, overview papers by Hock (2005) and Oerlemans et al. (2007) provide reviews on available scaling approaches and regional climate model driven glacier modelling efforts, respectively. In terms of thermosteric sea level rise, both the diagnosis of the existing CMIP3 archive as well as the forthcoming CMIP5[25] archive of coupled model intercomparisons will provide a wealth of detail, although substantial uncertainties are likely to remain.

2. What are the relative advantages and reliability of process-based and semi-empirical methods of projecting 21st century global sea level change? Can we combine them somehow? If there is a gap in the sea level budget of the past, how should we deal with it for the future?

The breakout group discussed in particular how to treat a gap between modelling capabilities and observations, in the case that such a gap will exist at the time of the AR5. Such a gap of 0.7 mm/yr was acknowledged in the AR4, but did not inform future projections. Furthermore the size and uncertainty of any gap depends on the time horizon considered, with the gap for recent years including a zero gap possibility within its uncertainty band.

If there is any gap, the key question is how to use or not use it to inform future projections. As a first approximation, semi-empirical models scale the gap with future temperatures. Not scaling the gap with temperatures, but rather to provide future sea level rise projections without closing the gap, has been the approach in the AR4. Without the knowledge about the underlying physical processes that are causing the discrepancy between current observations and modelling efforts, it is difficult to judge which approach is correct. In fact, probably neither approach can be judged to be correct, as long as the gap is not closed by an improved physical understanding of the current sea level rise contributions.

The semi-empirical models lack the physical basis to such a degree, that their projections can only provide a rough first order approximation of future global sea level rise. With this caveat in mind, the view was expressed that semi-empirical models might possibly be used to inform the upper bound of future projections. However, the consensus within the group was that semi-empirical models on their own should not be used to provide the AR5’s best estimate projections.

3. Given that AOGCMs disagree with each other about patterns of sea level change, and with observations, what can we do for regional projections of mean sea level change?

The group considered contributions to regional sea level rise without coming to a final ranking in regard to their importance, uncertainty, or the respective modelling capacity.

First, a set of regional contributions will likely be based on forthcoming CMIP5 models, namely dynamic effects due to changing ocean currents, and the intrinsically related changes in thermosteric and halosteric patterns.

Second, regional sea level variations resulting from crustal deformation, gravity and rotational effects resulting from mass redistribution, primarily those of the land ice masses (Greenland, West Antarctic Ice Sheet, East Antarctic Ice Sheet and Glaciers and Ice Caps) can be accounted for via well understood modelling techniques. Uncertainties in resulting sea level change patterns arise from initial uncertainties in mass distributions. GIA will also be a determining factor for deriving regional sea level patterns. While imperfect, the uncertainties in GIA estimates can be assessed by comparing different GIA predictions.

4. Can we make projections of changes in extremes?

Traditionally, the standard approach was to estimate changes in extremes simply by adjusting the baseline level of sea levels, adding the frequency spectrum and amplitudes of currently observed extremes. Whether there exists a more encompassing approach, which takes into account changes in local extreme event characteristics, remains an open

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[25] http://cmip-pcmdi.llnl.gov/

question. For the WGI contribution to the AR5, close cooperation with the regional climate process chapter will be necessary, e.g., in regard to tropical cyclone frequencies and intensities (Chapter 14).

5. Are the limits of reliability for future projections the same for all latitudes and/or regions?

No.

6. How should we make projections for scenarios that AOGCMs have not simulated? How should the uncertainty on projections be assessed?

Due to time constraints, the breakout group was unfortunately not able to cover this issue beyond considering the approach taken within the AR4.

7. How far into the future is it helpful to make projections?

Options for the time horizon are for example, 2080-2099, 2100, 2200, 2500, or even projections all the way to equilibrium conditions. The group acknowledged that the appropriate time horizon is largely driven by user-needs. Some users have to rely upon very short-term projections, while other larger infrastructure projects require projections on a century time scale and beyond. From a WGI perspective, the question arises at what time horizons can projections or predictions be reliably provided. It was raised that very long-term projections on geological timescales (equilibrium conditions) might be – in some cases – 'easier' than transient simulations of global sea level rise. This, however, ties in with the question of where potential thresholds in ice sheet stabilities lie (see Breakout Group 7). It is currently unknown, at which level such potential thresholds of irreversible ice sheet disappearance on multi-thousand year timescales could arise. Once these threshold levels are crossed, it might not be possible for the ice sheets to re-grow without a substantial drop in temperatures, even below pre-industrial levels.

8. Can we provide sea level projections (global and regional) on decadal time scales (from AOGCMs)? How accurate will those be?

The skill of short-term predictions was briefly discussed, with the view expressed that the skill of short-term predictive runs will not extend beyond a decade or so.

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Breakout Group 7: Ice Sheet Instabilities: Understanding and Projections

Chair: David Vaughan, British Antarctic Survey, United Kingdom
Rapporteur: Shawn Marshall, University of Calgary, Canada

Framing Statement

Several positive feedbacks, thresholds and tipping points have been identified that if initiated or reached would lead to the substantial and/or irreversible loss of portions of Antarctic and Greenland ice sheets, and consequent sea level rise. Such changes may be expected to be initiated by (atmospheric or oceanic) climate forcing while others might be initiated by internal, or long-term natural change. These 'instabilities' have contributed to the difficulties that IPCC has encountered in estimating the maximum likely rate of sea level rise by 2100, and will be addressed in the AR5. This breakout group was intended to provide a basis for that discussion.

1. Which are the most concerning of these 'instabilities', and what are the areas of the ice sheet to which they pose the greatest risk?

- Marine ice-sheet grounding lines (instability, non-linear response to forcing)
- Surface elevation – mass balance (threshold, commitment to long-term change)
- Ice-shelf response to atmospheric/oceanic forcing (non-linear/catastrophic response), with the potential to trigger acceleration and drawdown of inland ice
- Melt-lubrication of glacier and ice-sheet flow
- Albedo feedbacks of increased melt, with an expanded, darker ablation area leading to increased melt rates

2. What are the specific threats that the instabilities pose?

- Rapid sea level rise
- Commitment to long-term sea level rise
- Potential disruptions to ocean circulation

3. What are diagnostic changes [observations?] that would lead us to increase/decrease our estimation of the risk that these systems are entering states of positive feedback?

Although, the marine ice-sheet 'instability' is a notable exception, there is an improving understanding of the thresholds that must be exceeded to produce significant responses. These come from improved observations, supported by modelling in many forms.

4. Are there programmes of research, back-of-the-envelope calculations, or palaeo-analogues that could be used to identify the likelihood and maximum rates of sea level rise that should be expected from the instabilities?

We highlight that developing a demonstrable skill in ice-sheet projection is hampered by a lack of data and observations for verification and testing. This is particularly acute for the marine ice-sheet instability. Improved geological histories of ice-sheet changes and the forcing that caused them could greatly assist in building such a skill. In particular, a better understanding of the sources of Melt Water Pulse 1a would be extremely valuable. Similarly, the rates of sea-level rise during Marine Isotope Stage 5e would provide a strong analogue for future change. Idealized 'end-member' modelling scenarios could also help to provide limits on the likely maximum rate of sea-level rise from ice sheet instabilities, but the 'most likely' response of the ice sheets remains difficult to quantify.

5. What active research programmes could deliver greater certainty into these risks? Identify gaps in the global research programme?

Several major programmes with ambitions to contribute to the AR5 are now underway. SeaRISE and ice2sea, in particular, have complimentary approaches, but comparison of their parallel projections will directly contribute towards assessments of uncertainty.

6. How could quantitative projections, or ranges of uncertainty, for future sea level contributions from these processes be made?

It is unlikely, that we will be in a position to put an absolute upper bound on the contribution of ice sheets to sea-level rise from a consideration of physically-based models alone. However, the use of extrapolations based on recent, historical and geological observations, must be shown to be physically plausible and this can only be done with reference to the improving glaciological understanding. Considerable progress is undoubtedly being made and will be delivered for the AR5.

Discussion

During the breakout group, there was an expression of concern regarding the definitions of terms, such as 'instability', 'thresholds', 'non-linear responses', 'positive feedbacks' and 'tipping points' as applied to ice sheets. Similarly, much was made of the distinction between true 'instabilities' and processes that are merely subject to positive feedbacks, as well as issues concerning the timescales of forcing and response. We concluded that the term 'instability' is now being routinely applied to ice-sheet processes that do not fit the strict mathematical definition of 'instability', but represent a raft of process-types given above; this may be a 'shorthand' that is useful to communication of the broader issues. However, distinctions do need to be made; for example, some processes only have significant long-term impacts on ice sheets if forcing is sustained (e.g., surface mass balance losses driven by increasing summer temperatures), whereas others really do imply instability, such that once an internal/external threshold has been exceeded, there follows an irreversible response. More correctly, we might term the collective issues as, 'perturbations from which it is difficult to recover'.

Given these concerns, there was a clear general agreement that this was a distraction from the essential point – a point of consensus – that ice sheets are capable of highly nonlinear dynamical behaviour that could contribute significantly to short-term sea level rise (to 2100), and may also produce a long-term commitment (e.g., centuries-long) to substantial (many metres) of sea level rise.

When considering the future of the ice-sheet instabilities, we must consider how they will be initiated, sustained, and exacerbated by the various drivers of ice-sheet change: anthropogenic climate change, internal instability, or responses to long-term (natural) climate change. Each of these drivers may have a role to play, and together they represent a significant threat to portions of both Antarctic and Greenland ice sheets.

We discussed several candidate instabilities and concluded that the main one of concern is the so-called marine ice-sheet instability (or tidewater instability). This instability has been seen to operate on tidewater glaciers that have over-deepened beds, and could operate similarly on ice-sheet margins that have beds which deepen inland. This is a true, positive feedback process; thinning and acceleration of ice-flow as an ice front or grounding line retreats inland causes drawdown of the inland ice sheet and propagation into the ice sheet interior. The timescale, sea-level rise potential, and the triggers for potential instabilities vary between basins, and generalizations are difficult. All of the West Antarctic Ice Sheet or Greenland would not be expected to destabilize at once, but important areas of each ice sheet are vulnerable to this instability, and could add significantly to decadal and century-scale sea-level rise.

Two-dimensional, flow-line models have improved in their grounding line treatments such that we can now simulate the process and its inland propagation and limits reasonably well, but fully three-dimensional models need to be run to capture the potential stabilizing influence of 3D flow dynamics and bed topography. Regional 3D simulations are expected to be available for the AR5, as well as simplified 'what-if' whole-ice sheet simulations that explore idealized scenarios for grounding line retreat (e.g., Ritz, 2001). These will provide initial upper bounds of sea level rise through this process, but some important processes and boundary-condition data are still missing in the whole-ice sheet models, such as adaptive grids to track the position of the grounding line, detailed basal topography and bathymetry, oceanic boundary conditions, and several aspects of ocean-ice interactions. We know reasonably well the way in which marine-based ice will respond to a given ocean temperature change, but the future ocean warming scenarios in sub-ice shelf cavities and the coupled ocean-ice models are not yet available to explore this process deterministically for the AR5.

Similar issues apply to ocean forcing of iceberg calving at marine margins, as this mechanism can induce ice-shelf loss and allow consequential loss from the interior ice sheet. We discussed whether this should be considered as part of the marine grounding line instability, but there are reasons to keep it separate. For instance, ice shelf breakup can also proceed via air-temperature forcing/meltwater-induced weakening, and we have reasonable predictive ability for this process. It is also uncertain whether or not there would be sustained speedup and thinning of outlet glaciers and ice streams that feed ice sheet margins upon removal of an ice shelf, as this depends on the bed topography and flow dynamics of the inland ice.

Other ice sheet instabilities were deemed secondary compared to these, and may not qualify as true instabilities but rather, positive feedback processes, or simply non-linear responses. These include meltwater lubrication of basal flow, melt-albedo feedbacks on surface mass balance, and surface mass balance-elevation feedbacks, where declining mass balance causes an expanding ablation area and lower ice sheet elevations, hence further declines in surface mass balance. All of these processes are important in Greenland and are expected to play a role in increasing ice sheet runoff in warmer climate conditions. It is believed that the AR4-class models do a good job of quantifying the surface mass balance-elevation feedback, which starts slowly but will likely become significant post-2100. This process, in particular, represents an important amount of 'commitment' to sea level rise if temperatures warm to the point where surface mass balance becomes negative in Greenland. We do not yet have good numbers for the extent of extra sea level rise associated with meltwater lubrication or lowering ice sheet albedo in a warmer world. Those present generally believed these to be unimportant and a low priority for the AR5, but this is speculative, as these processes are absent or weakly parameterized in whole-ice sheet simulations to date.

Finally, much is made of the lack of demonstrable predictive skill for ice sheets, because uncertainty in this area can be argued to dominate uncertainty in prediction of sea level, but this lack of skill is mirrored elsewhere in the climate system. For example, many possible impacts of anthropogenic climate change on the oceans are at present very poorly understood. The lack of predictive skill for ice sheets results only in part from an incomplete understanding of ice-sheet processes, and is also due to incomplete representation of ice-atmosphere and ice-ocean processes in models, a lack of data and/or observations against which skill can be demonstrated, and indeed, an inherent lack of predictability in the system. Models cannot be 'spun-up' in a simple way, as the internal dynamics of ice sheets and their 'secular trends' reflect ice sheet and bedrock evolution over time scales of 10 years. The long response times of ice sheets put specific constraints on ice-sheet projection, since current observations capture only a very short period of change. An accurate spin-up is needed to effectively capture patterns and rates of change in recent periods and for model projections.

Specific Ice-Sheet Instabilities

Although there may be other non-linear responses, feedbacks and instabilities in ice-sheets, the following descriptions summarise the most significant issues identified in the breakout group.

Marine Grounding Line/Tidewater Instability

Instability in tidewater glaciers has been seen many times to cause rapid retreat of the terminus through an area of over-deepened bed. The same instability is expected to be realized in ice sheets, although contemporary observations of such behaviour are lacking, and geological evidence remains contested. Instability in ice-sheet margins has been demonstrated in 2D models (e.g., Pine Island Glacier) but there are likely to be some 3D stabilizing influences. The importance of specific basin shapes is thus difficult to determine, and makes it hard to generalize. Buttressing by ice shelves could slow retreat down, but these are climate-sensitive features and their removal by atmospheric and/or ocean change could trigger retreat. Tidewater glacier (in)stability itself is not debated, but is highly related, and could provide a valuable analogue/training ground for marine ice sheets, although retreat of tidewater glaciers may be triggered by different conditions in different basins. One lesson from recent behaviour of tidewater glaciers, is that we expect retreat to be punctuated by periods of stasis, reduced retreat representing a stepped-retreat.

Episodic behaviour seems to be the norm. It is a characteristic of the system and it is something that can lead to cumulative, integrative impacts (including, sea-level rise) if acting in concert (i.e., if responding to forcing).

Surface Mass Balance – Elevation Effect

The lowering of an ice-sheet, leads to change in the balance between accumulation and ablation zones. If lowering of the margins leads to drawdown of the interior, a state can be entered where the net accumulation is insufficient to maintain the ice sheet, and if conditions persist, an extended retreat of the ice sheet may be inevitable. This may not be a true instability, but represents a very clear threshold. The surface mass balance-elevation effect is well recognized in models of small ice caps, where it is an equilibrium response to a persistent change in boundary conditions. The process has also been shown in projections of the Greenland ice sheet. Here, the timescale of forcing and response is critical, on the short timescale (decades), the ice-sheet response to changing climate may appear linear, but over longer timescales (centuries), it may look more like a non-linear response, or a threshold. However, in each case, it currently appears that the forcing needs to be maintained if the positive feedback is to become significant, and so the effect is reversible if climate were to recover sufficiently early, although growth of the ice sheet might be considerably slower than the initial loss.

The degree to which melt-albedo feedbacks accentuate this issue is not yet resolved, as the coupling between ice sheet and atmospheric models used for projections is relatively simplistic (e.g., degree-day models of snow and ice melt, rather than a full energy balance).

Ice Shelf Collapse – Ice Sheet Drawdown

Given the stabilizing influence of ice shelves on the ice sheets to which they are attached, and the catastrophic responses to climate change that have been observed in ice shelves over the last few decades, the coupled ice-shelf – ice-sheet system is particularly prone to dramatic retreat. Furthermore, given the potential for change in the ice-marginal ocean system, that might themselves be subject to rapid change, or 'instabilities', there is the potential for significant changes in some areas. Given the complexity of the interactions between atmosphere and oceans, and oceans and sea, there is limited likelihood of projective skill being developed prior to the AR5.

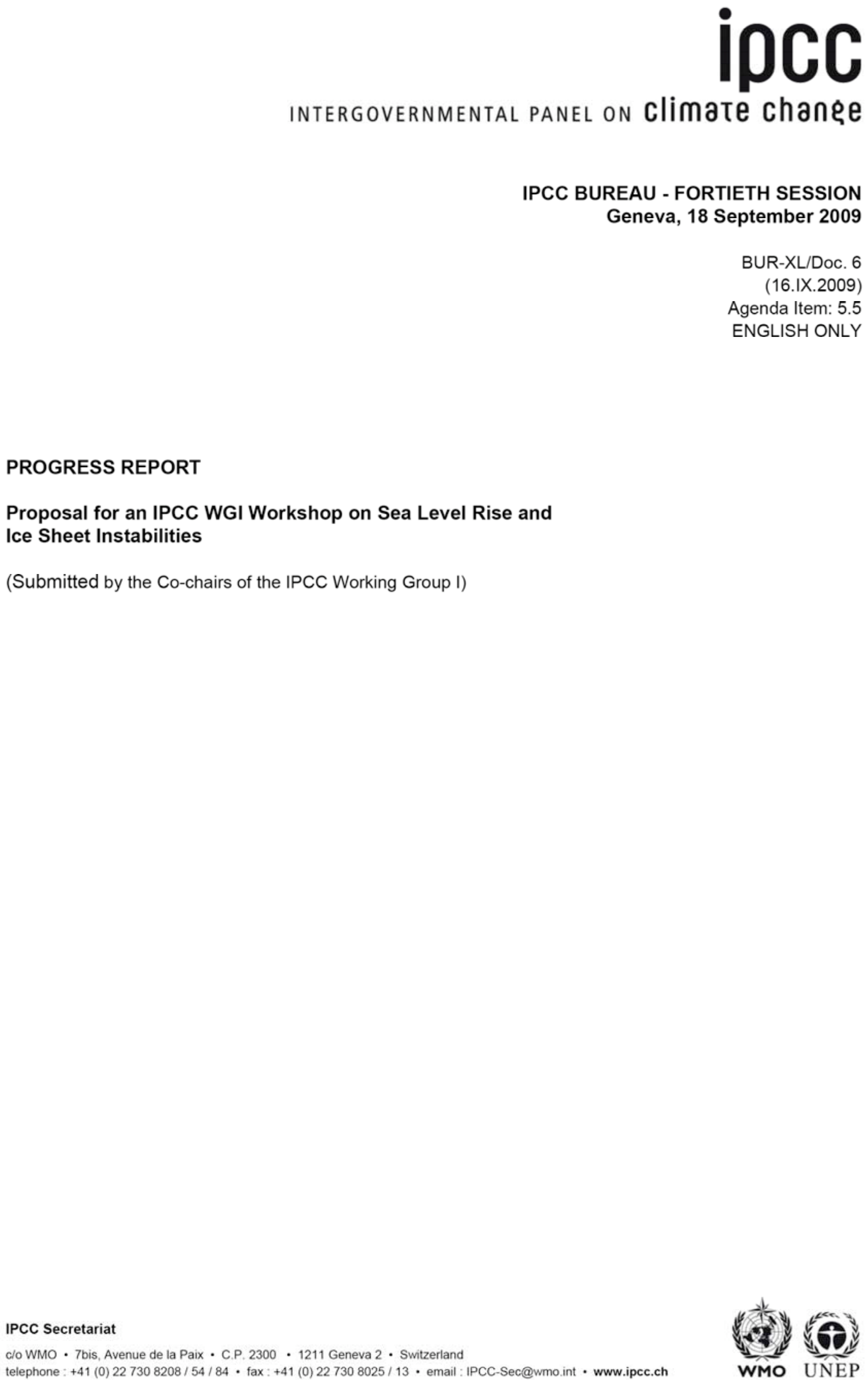
Melt-Lubrication - Increased Flow of Outlet Glaciers

Much has been made of the possibility that warming atmospheric climate will lead to increasing supply of meltwater to an ice-sheet bed, leading to greater flow-speeds and loss of ice. This effect appears to be a near-term possibility only in Greenland where significant surface melt occurs. We have a reasonable understanding of the likely magnitude of the impacts of this process within the next few decades, but in time this process may become more important, and will likely spread substantially in influence, and in this regard there is considerably less skill in predictions.

References

Ritz, C., V. Rommelaere, and C. Dumas, 2001: Modeling the evolution of Antarctic ice sheet over the last 420,000 years: implications for altitude changes in the Vostok region. *J. Geophys. Res.-Atmos.*, **106**(D23), 31943-31964.

Annex 1: Proposal



ipcc
INTERGOVERNMENTAL PANEL ON climate change

IPCC BUREAU - FORTIETH SESSION
Geneva, 18 September 2009

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Agenda Item: 5.5
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PROGRESS REPORT

Proposal for an IPCC WGI Workshop on Sea Level Rise and Ice Sheet Instabilities

(Submitted by the Co-chairs of the IPCC Working Group I)

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Proposal for an IPCC WGI Workshop on Sea Level Rise and Ice Sheet Instabilities

Submitted by the Co-chairs of IPCC Working Group I

Background

Among the major long-term consequences of climate change is global sea level rise. A reliable projection is required in order to quantify coastal impacts and to assess the sustainability of coastal settlements around the world. In particular, small islands are already now affected by rising sea level and therefore a reliable estimate of future rates of increase of sea level is crucial. Sea level rise is caused by a number of processes with contributions from: (i) thermal expansion of the ocean, (ii) melting of glaciers and small ice caps, (iii) melting of Greenland and Antarctica, (iv) changes in ocean circulation, and (v) changes in water storage on land. Both the size and the uncertainty of each of these contributions need to be quantified in order to make a useful projection of global sea level rise and its regional expression.

The Fourth Assessment Report of IPCC (AR4) has shown that melting of polar ice caps substantially contributes to the observed sea level rise, but that major limitations exist in the scientific understanding of the response of the two large polar ice sheets, Antarctica and Greenland, to the direct effects of surface warming and changes in accumulation (snow fall) as well as to indirect effects such as subsurface ocean warming and sea level rise feedback. This is the primary reason for the large uncertainty in the AR4 projections of sea level rise for the 21st century. The possibility of ice stream and whole ice sheet instabilities that may be triggered by slow changes in the forcing adds additional uncertainty. In particular, renewed discussion of instabilities of the West Antarctic Ice Sheet and of thresholds for a Greenland ice sheet meltdown requires comprehensive assessment. The lack of both scientific understanding and a sufficient observational base concerns primarily ice sheet-bedrock interactions as well as ice sheet hydraulics.

WGI has acknowledged the policy relevance of this specific topic and has proposed a chapter on "Sea Level Change" in its contribution to the Fifth Assessment Report of IPCC (AR5). In order to discuss the current understanding comprehensively across various scientific disciplines, ranging from oceanography, ice sheet dynamics, and glacier research, WGI proposes to the IPCC Plenary to organize an IPCC Workshop on "Sea Level Rise and Ice Sheet Instabilities" to be held in mid-2010. In order for this workshop to produce input to the assessment process of WGI already at an early stage, the timing is critical. Projections of sea level rise require the combination of information from various different fields, and therefore robust procedures with respect to estimating uncertainties should also be discussed in this workshop.

Aims of Workshop

- Bring together the leading world experts on all issues related to sea level rise, including the field of ice sheet dynamics and ice sheet instabilities, in order to accelerate scientific research that will feed results into the AR5;
- Collect and discuss the latest results from observations related to sea level rise from oceanographic, cryospheric and paleo records, including information on thermal expansion of the ocean, melting of glaciers and small ice caps, changes in the mass balance of Greenland and Antarctica, changes in ocean circulation, and changes in water storage on land;

- Expose the current understanding, and limitations, of ice sheet and ice stream dynamics, including information on their sensitivity to changes in the forcings and on potential irreversibility associated with ice stream or whole ice sheet instabilities;
- Critically evaluate modelling tools used to project sea level rise, the resulting projections, and assess and constrain associated uncertainties.

Organizing Group (about 5-6 members)

Thomas Stocker (WGI Co-Chair, Switzerland)
Dahe Qin (WGI Co-Chair, China)
Richard Alley (Ice Sheet Instabilities, USA)
Annie Cazenave (Sea Level Rise, France)
Leonard Nurse (Small Island State Representative, Barbados)
Fredolin Tangang (WGI Bureau, Malaysia)

A Scientific Steering Committee with broad representation will be formed.

Timing: week beginning 21 June 2010 (tbc)

Duration: 4 days

Location: Malaysia (tbc)

Participants

About 120 participants (experts) in total. In order to ensure broad international representation, it is proposed that there should be a call for governments to nominate scientific experts to attend the workshop. The budget proposed for adoption at IPCC-XXXI includes an allocation of 40 journeys for experts from developing countries and economies in transition including the WGI Vice-chairs. This allocation was tentatively agreed at IPCC-XXX as part of the line item “Workshops related to the AR5” in the already agreed IPCC Trust Fund budget for 2010.

Expertise

Ocean observations and remote sensing of ocean changes, sea level observations, tide gauges, direct measurements on, and remote sensing of, polar ice sheets, ice sheet dynamics, ice sheet-bed rock-ocean interaction, changes in water reservoirs on land, paleo ice sheet reconstruction, models of sea level rise, ice sheet models.

Annex 2: Programme

IPCC Workshop on Sea Level Rise and Ice Sheet Instabilities

Hilton Hotel, Kuala Lumpur, Malaysia
21-24 June 2010

PROGRAMME

Sunday, 20 June 2010

18:00–19:30 **Early Registration and Welcome Reception** *(Sponsored by the IPCC WGI TSU)* *(Boardwalk Restaurant/Poolside Area)*

Monday, 21 June 2010

08:30 Registration *(Lake Garden Foyer)*

OPENING PLENARY *(Ballroom A)*

09:00–10:00 **Welcome and Opening:** *Prof. Dr. Thomas Stocker, Co-Chair, IPCC Working Group I*

Welcome Remarks:

- *Prof. Dr. Fredolin Tangang, IPCC Working Group I Vice-Chair and Head of the Local Organizing Committee*
- *Dr. Rajenda Pachauri, Chair, IPCC*
- *Prof. Tan Sri Dato' Dr. Sharifah Hapsah Syed Hasan Shahabudin, Vice-Chancellor, National University of Malaysia*
- *Datuk Aziyah Mohamad, Deputy Secretary General, Ministry of Natural Resources and Environment, Malaysia*

10:00 Break *(Lake Garden Foyer)*

INTRODUCTORY PLENARY *(Ballroom A)*

10:30 ***Sea Level Change from TAR to AR5*** **(Thomas Stocker)** [15 min presentation]

THEME PLENARY I: GREENLAND – MASS BALANCE, DYNAMICS, AND CONTRIBUTIONS TO SEA LEVEL RISE [Chair: Thomas Stocker] *(Ballroom A)*

10:45 ***Greenland Mass Balance: Observations, Modelling and Uncertainties*** **(Konrad Steffen)** [20 min presentation + 10 min discussion]

11:15 ***Dynamics of the Greenland Ice Sheet: Observations and Potential Instabilities*** **(Eric Rignot)** [20 min presentation + 10 min discussion]

11:45 ***Ice Sheet – Ocean Interactions and Implications for Melting and Instabilities*** **(David Holland)** [20 min presentation + 10 min discussion]

12:15 Lunch

THEME PLENARY II: GLACIERS AND ICE CAPS – MASS BALANCE, DYNAMICS, AND CONTRIBUTIONS TO SEA LEVEL RISE [Chair: Jean Jouzel] ***(Ballroom A)***	
13:30	***Glacier Contributions to Sea Level Rise: Past, Present and Future*** **(Georg Kaser/Tad Pfeffer)** [20 min presentation + 10 min discussion]
14:00	***Global Glacier Mass Balance: Modelling and Uncertainties*** **(Roderik van de Wal)** [20 min presentation + 10 min discussion]
POSTER SESSION I [Chair: Thomas Stocker] ***(Ballroom A)***	
14:30	**Poster Presentations** [2 min presentation with one ppt slide]
15:30	**Break** ***(Lake Garden Foyer)***
POSTER SESSION I (CONTINUED) ***(Ballroom B)***	
16:00	**Poster Session**
18:00	**Adjourn**

Tuesday, 22 June 2010

THEME PLENARY III: ANTARCTICA – MASS BALANCE, DYNAMICS, AND CONTRIBUTIONS TO SEA LEVEL RISE [Chair: Qin Dahe] ***(Ballroom A)***	
08:30	***Satellite-Based Observations of Sea Level Rise from Large Ice Sheets*** **(Isabella Velicogna)** [20 min presentation + 10 min discussion]
09:00	***Dynamics of the Antarctic Ice Sheet: Observations and Potential Instabilities*** **(Tony Payne)** [20 min presentation + 10 min discussion]
09:30	***Factors Limiting Precise Knowledge of the Current and Future Mass Balance of the Antarctic Ice Sheet: Present Status and Steps Forward*** **(Ian Allison)** [20 min presentation + 10 min discussion]
10:00	**General Discussion Themes I-III: Greenland, Antarctica, Glaciers**
10:30	**Break** ***(Lake Garden Foyer)***
POSTER SESSION II [Chair: Pauline Midgley] ***(Ballroom A and B)***	
11:00	**Poster Presentations** ***(Ballroom A)*** [2 min presentation with one ppt slide]
11:30	**Poster Session** ***(Ballroom B)***
13:00	**Lunch**
THEME PLENARY IV: OCEAN: DENSITY AND CIRCULATION CHANGES [Chair: Susan Wijffels] ***(Ballroom A)***	
14:30	***Changes in Ocean Properties Influencing Sea Level: Observations, Modelling and Uncertainties*** **(Sarah Gille)** [20 min presentation + 10 min discussion]
15:00	***Influence of Ocean Circulation Changes on Sea Level: Observations, Modelling and Uncertainties*** **(Detlef Stammer)** [20 min presentation + 10 min discussion]
BREAK-OUT GROUP SESSION I [refreshments available 15:30-16:00 in Lake Garden Foyer]	
15:30	**BOG 1: Ice Sheets: Greenland [Chair: Waleed Abdalati; Rapporteur: Andreas Vieli]** ***(Sentral Ballroom A)*** **BOG 2: Ice Sheets: Antarctica [Chair: Bob Bindschadler; Rapporteur: Andrew Shepherd]** ***(Sentral Ballroom B)*** **BOG 3: Glaciers and Ice Caps [Chair: Georg Kaser; Rapporteur: Jens-Ove Hagen]** ***(Sentral Exchange A)*** **BOG 4: Thermal Expansion and Halosteric Effects [Chair: Susan Wijffels; Rapporteur: Syd Levitus]** ***(Ballroom A)***
17:30	**Reports from Break-Out Groups 1-4 (BOG Chairs) and Discussion [Chair: Qin Dahe]** ***(Ballroom A)***
18:30	**Adjourn**
19:00	**Gala Dinner** ***(Sponsored by the Universiti Kebangsaan Malaysia and the Ministry of Natural Resources and Environment of Malaysia) (Sentral Ballroom A and B)***

Wednesday, 23 June 2010

	THEME PLENARY V: OCEAN: OBSERVED SEA LEVEL CHANGE [Chair: David Wratt] ***(Ballroom A)***
08:30	***Records of Past Sea Level Change: Amplitudes and Rates*** **(Edouard Bard)** [20 min presentation + 10 min discussion]
09:00	***Sea Level Budget Over the Past Few Decades and Recent Years: A Review*** **(Anny Cazenave)** [20 min presentation + 10 min discussion]
	THEME PLENARY VI: PROJECTIONS OF SEA LEVEL RISE AND UNCERTAINTIES [Chair: David Wratt] ***(Ballroom A)***
09:30	***Projections of Sea-Level Rise: From Global to Regional Scales*** **(Jonathan Gregory/Jason Lowe)** [20 min presentation + 10 min discussion]
10:00	***Sea Level Rise Projections From Semi-Empirical Models*** **(Svetlana Jevrejeva)** [20 min presentation + 10 min discussion]
10:30	**Break** ***(Lake Garden Foyer)***
	POSTER SESSION III [Chair: Gian-Kasper Plattner] ***(Ballroom A and B)***
11:00	**Poster Presentations** ***(Ballroom A)*** [2 min presentation with one ppt slide]
11:30	**Poster Session** ***(Ballroom B)***
13:00	**Lunch**
	BREAK-OUT GROUP SESSION II [refreshments available 15:30-16:00 in Lake Garden Foyer]
14:30	**BOG 5: Accounting for Past Sea Level Change [Chair: Philip Woodworth; Rapporteur: Yusuke Yokoyama]** ***(Sentral Ballroom A)*** **BOG 6: Projections of Global and Regional Sea Level Change [Chair: Leonard Nurse; Rapporteur: Malte Meinshausen]** ***(Ballroom A)*** **BOG 7: Ice Sheet Instabilities: Understanding and Projections [Chair: David Vaughan; Rapporteur: Shawn Marshall]** ***(Sentral Ballroom B)***
16:30	**Reports from Break-Out Groups 5-7 (BOG Chairs) [Chairs: Qin Dahe and Thomas Stocker]** ***(Ballroom A)***
17:00	**Break-Out Groups 1-7 Discussion**
18:30	**Adjourn**

Thursday, 24 June 2010

SYNTHESIS PLENARY [Chair: Thomas Stocker] ***(Ballroom A)***	
08:30	***Past and Present Sea Level Changes: Key Conclusions and Way Forward*** **(John Church)** [30 min presentation + 15 min discussion]
09:15	***Future Sea Level Changes: Key Conclusions and Way Forward*** **(Jonathan Gregory)** [30 min presentation + 15 min discussion]
10:00	**Break** ***(Lake Garden Foyer)***
10:30	**Open/General Discussion**
12:30	**Closing Remarks (Thomas Stocker)**
13:00	**End of Workshop/Closing Reception** ***(Lake Garden Foyer)***

Annex 3: Extended Abstracts

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† Invited Keynote
**Poster Presenter*

Ice Cloud and Land Elevation Satellite-2 (ICESat-2): Advancing the Understanding of Ice Sheet Contributions to Sea Level Rise

Waleed Abdalati

Cooperative Institute for Research in Environmental Sciences, University of Colorado, USA

Our understanding of ice sheet contributions to sea level rise has changed dramatically in the past decade, as satellite and aircraft observations have brought into sharp focus how quickly ice sheets respond to present day forcings. These responses, in particular those related to ice dynamics, have revealed rapid changes in outlet glacier and basin-scale mass balance, suggesting a possible transition to a new regime of ice sheet behavior. These same observations have also revealed significant limitations in our ability to model this behavior. In light of these recent revelations, it is clear that sustained observations are essential for determining current ice sheet contributions to sea level rise and understanding what they may be in the future. Toward that end, NASA is planning to launch its Ice, Cloud and land Elevation Satellite-2 (ICESat-2) mission, in 2015.

ICESat-2 (Figure 1) is a multi-disciplinary mission, with examining ice sheet mass balance as its primary objective. It will accomplish this by building on the ground-breaking capabilities of its predecessor, ICESat, precisely measuring ice sheet elevation changes and their variation in time and space. The temporal and spatial variation is an important component of this mission, as the different mechanisms of change have distinct topographic signatures, which the ICESat-2 data will help to unravel. As a result, sampling density is a very important consideration in the mission design.

ICESat-2 is planned to operate in a nine-beam configuration with three sets of closely-spaced triplets. Each triplet will measure local cross-track slope in addition to elevation change, which will greatly improve change-detection accuracy and enable assessment of its evolution with time. The three sets of triplets will also improve the spatial and temporal sampling density significantly. Through precise pointing and orbit control and knowledge, ICESat-2 will measure change along repeat tracks as well as at very dense crossovers. As a result, we expect ICESat-2 to be capable of resolving winter/summer elevation change to 10 cm at sub-drainage basin scales (25 km x 25 km), and annual elevation changes of 25 cm/yr on outlet glaciers (100 km2 areas) and along shear margins. Moreover, the simultaneous observations of elevation and cross-track slope, will substantially improve the sampling and accuracy of the rapidly-changing outlet glaciers.

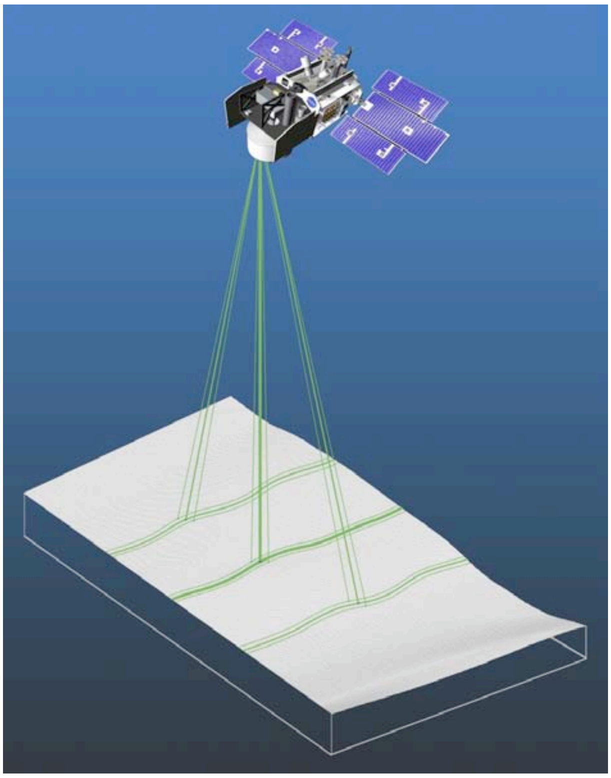

Figure 1. Representation of the ICESat-2 mission. Its nine beams consist of three sets of closely-spaced triplet. Each triplet measures local cross-track slope.

With a five year continuously operating mission life, ICESat-2 will provide the detailed elevation change measurements needed to truly understand how and why the ice sheets are changing. When combined with observations from the original ICESat mission, as well as complementary observations such as those from Cryosat-2, GRACE, the various interferometric synthetic aperture radar missions, and airborne campaigns, ICESat-2 will provide essential insights not only how the ice is changing now, but more importantly, how it will change in the future.

Factors Limiting Precise Knowledge of the Current and Future Mass Balance of the Antarctic Ice Sheet: Present Status and Steps Forward

Ian Allison

Antarctic Climate and Ecosystem Cooperative Research Centre, Australia

Over the last decade or so, space-based techniques (altimetry, gravimetry and estimates of the difference between annual mass input and output) have provided clear evidence of increasing mass loss from the West Antarctic ice sheet and the Antarctic Peninsula, although there remain differences between the mass balance estimates from different techniques. In the case of the much larger East Antarctic ice sheet there is also clear evidence of increased discharge from a number of major outlet glacier systems, but remaining uncertainty to whether the overall mass balance is positive or negative. The causes for accelerated ice discharge of outlet systems in both West and East Antarctica, and in particular whether the changes are linked to anthropogenic warming, are also unclear.

Extrapolation of the present rate of discharge, or of the current rate of increase of discharge, over the next century provides a useful indication of the potential upper limit of the sea level contribution from the Antarctic Ice sheet. More accurate projections of future slr however, require improved ice sheet models that properly account for the causes of change. Such models are being developed by a number of international consortia. The models require better understanding of processes such as ice sheet-bed interactions, and more comprehensive and higher resolution data on the ice sheet boundary conditions, and data to validate the modelling initiatives. Several large-scale Antarctic surveys commenced during, and continuing beyond, the International Polar Year are contributing to these.

Sea Level Change Along the Italian Coast During the Holocene and Projections for the Future

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Sea-level change is the sum of eustatic, glacio–hydroisostatic and tectonic factors. The first is global and time dependent, while the other two also vary according to location. The glacio–hydro-isostatic factor along the Italian coast was recently predicted and compared with field data, at sites not affected by significant tectonic processes (Lambeck et al., 2004a).

The Mediterranean Sea, a semi-enclosed basin, is a part of the world where sea level changes have played an important role in the past. Coastal sea level derived from the longest tide gauges indicates a rate of sea level rise for the 20th century of 1.-1.3 mm/yr (Marcos and Tsimplis, 2008), and 1.02±0.21 mm/yr for the Tyrrhenian coast of Italy (Lambeck et al., 2004b). For the period 1960 to 1990 an increase in the average atmospheric pressure over the basin caused negative sea level trends (Tsimplis and Baker, 2000; Tsimplis and Josey, 2002). We would highlight how the Mediterranean sea level change is less than the global estimates. Hence, the Mediterranean coasts should be at minor risk than those of the Oceans, but, on the other hand, isostatic and tectonic movements (mainly in the central north and east Med coasts) are still active and accelerate the impact on coastal changes. IPCC should enter into the merits of these regional issues.

In this research we use published (Ferranti et al., 2006, Antonioli et al., 2009) and new sea level data to provide projections of sea level change in Italy for the year 2100 by adding new isostatic and tectonic component to IPCC (2007) and Rahmstorf (2007) projections. The observational database includes besides tide gauge GPS analysis of the Mediterranean stations, geomorphological markers of palaeo sea level, coastal archaeological data, and sedimentary core analysis. Their age and elevation uncertainties are discussed and consistent calibration programs for the time scale and for the reductions of elevation measurements to mean sea level have been used. Comparison of the observations from more than 130 sites with the predicted sea level curves provides estimates of the vertical tectonic contribution to the relative sea level change. The results are based on the most recent model for the ice sheets of both hemispheres, including an alpine deglaciation model. On the basis of the eustatic, tectonic and isostatic components to the sea-level change, we provide for the year 2100 projections for marine inundation scenarios for the Italian coastal plains that today are at elevations close to current sea level.

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Figure 1. Relative sea level rise (year 2100) for 33 Italian coastal plains. For the Po Delta and Venice Plain we report a mean value. Data do not include the contribution of local soil compaction and fluid (gas and water) extraction (from Lambeck et al., 2010, *Quaternary International*.

The Sea Level Fingerprint of 21st Century Ice Mass Loss

Jonathan Bamber[1] and Riccardo Riva[2]

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[2] DEOS, Delft University of Technology, The Netherlands

The sea level contribution from glacial sources has been accelerating during the 21st Century. This contribution is not distributed uniformly across the world's oceans due to both oceanographic and gravitational effects. We compute the sea level signature of 21st Century ice mass fluxes due to changes in the gravity field and Earth's rotation. Mass loss from Greenland results in a relative sea level (RSL) reduction for much of North Western Europe and Eastern Canada. RSL rise from this source is concentrated around South America. Losses in West Antarctica marginally compensate for this and produce maxima along the coastlines of North America, Australia and Oceania. The combined far-field pattern of wastage from all ice melt sources, is dominated by losses from the ice sheets and results in maxima at latitudes between ±40° across the Pacific and Indian Oceans, affecting particularly vulnerable land masses in Oceania. Unlike steric and circulation-driven RSL variations, the spatial pattern of RSL due to the observed ice mass loss is temporally invariant. Thus, the long-term sea level rise from the present-day (and projected near future) distribution of ice loss will be amplified for this vulnerable region.

Records of Past Sea Level Change: Amplitudes and Rates

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Recording recent sea-level changes is particularly complex because local variations are often larger than the global average, and high-frequency changes are superimposed on long-term trends that even depend on the memory of pre-existing sea-level over an extended period of time. A complementary way of investigating the behavior of large ice sheets in response to climate change is to study the dramatic sea-level changes that occurred during deglaciations. Over such recent geological periods, sufficiently precise markers are available to measure the rate of sea-level change and the retreat of each individual ice sheet, notably the former Laurentide ice sheet.

Long time series of sea-level data are also crucial for constraining numerical models of glacio-hydro-isostasy (e.g., Milne & Mitrovica, 2008) that are used to reconstruct the location and size of previous ice-sheets and to correct the post-glacial rebound (PGR) component embedded in recent tide-gauge and satellite data (see Milne et al., 2009 and Cazenave & Llovel, 2010 for reviews). Furthermore, long sea-level records are of utmost importance as simulation targets for a wide spectrum of numerical models, ranging from three-dimensional thermomechanical ice-sheets to empirical relationships integrating a multitude of physical responses. The history of deglacial sea-level rise is also crucial to calculate the meltwater input to the ocean in climate models of various complexities (e.g., Liu et al., 2009, Renssen et al. 2009).

During the last glacial maxima, the global sea level was about 120-130 meters below the present-day level (e.g., Clark et al., 2009; Thomas et al., 2009). Glacial ice sheets subsequently disappeared over periods of 10-15 kyr (e.g. Dutton et al., 2009; Thomas et al., 2009; Bard et al., 2010). The rate of sea-level change was not constant throughout these periods, for example during the acceleration called Melt Water Pulse 1A of the last deglaciation. During this event (Deschamps et al. 2009), the sea-level apparently rose by several meters per century, (i.e., freshwater input to the ocean exceeding 1 Sverdrup = 10^6 m^3/s). This large hydrological perturbation probably impacted the Atlantic meridional overturning circulation.

Deglaciations are periods of first-order climate changes, fascinating for climatologists, since it allows them to study switches between equilibrium modes and transient variations at various spatial and temporal time scales. The implications of well-constrained data are numerous as boundary conditions for geophysical models and climate models. It is thus highly desirable to establish a comprehensive Quaternary sea level database.

These data are presently scattered across the scientific literature with widely varying reporting formats, screening and correction criteria, and decay constants. Stratigraphic information is often incomplete, and elevations are not tied to consistent benchmarks. It is highly desirable to compile existing data in a uniform format that can be made available to the wider community, and to adopt a uniform set of standards for future data reporting.

To address this problem the PALSEA international group aims to develop an open-access, quality-controlled database of relative sea level using consistent age estimates (Siddall et al., 2010; Thompson & Andersen, 2010). This will allow improvements in ice-sheet reconstructions in the future, which should be incorporated into climate simulations and PGR corrections of tide-gauge and satellite data.

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What's at Risk from Sea-Level Rise? Accommodating Adequate Sea-Level Rise Allowance into Decision-Making in New Zealand

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New Zealand's rate of relative sea-level rise (RSLR) since 1900 averages around 1.6 mm/yr across four main ports (Hannah, 2004). Subsequent analyses of these records and data rescue for three other long records indicate the RSLR still averages at 1.6 mm/yr ranging from 1.3 to 2.0 mm/yr (J. Hannah, pers. comm.) These historic RSLR rates, allowing for regional isostatic glacial adjustment, match closely with the historic global average eustatic rate. This means that global average sea-level rise projections to the end of this century are likely to be applicable for development decision-making.

Over the past year or so there has been a growing demand by local and regional councils in New Zealand for certainty and guidance on sea-level rise projections following the release of the IPCC Fourth Assessment Report (AR4), coinciding with the development phase of second-generation district and regional plans and regional policy statements. In response, New Zealand's Ministry for the Environment (MfE) released a revised 2nd Edition of the guidance manual for local government on *Coastal Hazards and Climate Change* (MfE, 2008). Demand for more certainty around what amount of sea-level rise should be accommodated in planning documents or engineering design is contrary to what currently science can provide, given a range of possible responses to warming by the world's major ice sheets. A summary of the IPCC AR4 projections along with more recent sea-level rise estimates, mostly using empirical approaches, was provided in the MfE Guidance Manual to further guide decision makers. In the meantime, planning must continue, so what sea-level rise value should be used for coastal development, infrastructure and other long term decision-making?

With such current uncertainty over the magnitude of potential sea-level rise this century, and the range of different types of decision-making that needs to take sea-level rise into consideration, a one-size fits all approach is not practical, robust or economical. Rather this question needs to be looked at in a different way, and can only be answered for any particular situation by considering what's at risk. Consideration of risk requires a broader consideration of the potential impacts or consequences of sea-level rise on a specific decision, objective or project. Rather than define a specific climate change scenario or single sea-level rise, the magnitude of sea-level rise accommodated needs to be based on the acceptability of the potential risk for the particular issue under consideration. In other words what sea-level rise is accommodated is an output of the process rather than a starting point (summarised conceptually in Figure 1) and is based on a balanced consideration between:

- the possibility of particular sea levels being reached within the planning timeframe;
- the associated consequences and potential adaptation costs; and
- how any residual risks would be managed for consequences over and above an accepted sea-level rise threshold, or if the accommodated sea-level rise is underestimated.

This is the fundamental approach underpinning the guidance provided in the New Zealand guidance manual (MfE, 2008), where for planning purposes and decision timeframes out to the 2090s:

1. A base value sea-level rise of 0.5 m relative to the 1980–1999 average should be used, along with….
2. **an assessment of potential consequences from a range of possible higher sea-level rise values** (particularly where impacts are likely to have high consequence or where future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of **at least 0.8 m** relative to the 1980–1999 average.
3. For longer planning and decision timeframes beyond the end of this century, an allowance for sea-level rise of **10 mm per year beyond 2100** is recommended.

Essentially part 1 provides an absolute minimum amount of sea-level rise to be accommodated in any situation where it is a factor, with part 2 suggesting that the sensitivity of the potential consequences and adaptation costs to a range of potential sea-level rise values be assessed and used to inform the amount of sea-level rise to be accounted for. In adopting such an approach a much more robust incorporation of sea-level rise and associated uncertainty can be accommodated within decision-making than can be achieved by using a single number. It is certainly not just a simple case of allowing for 0.8 m across the board. In all cases, the economic risk of choosing a particular sea-level rise needs to be assessed hand-in-hand with the knowledge that sea level rise will continue to accelerate into the future well beyond 2100 and being cognizant of the permanency of built assets and decisions on coastal subdivisions. Many councils around New Zealand have taken the guidance on board and are looking at the consequences of sea level changes like 0.5 m, 1.0 m, 1.5 m and more, and often not getting too concerned about a particular date to reach that RSLR. Therefore, the guidance has helped instigate a broader approach to adaptation planning that includes an assessment of risk rather than simply relying on a single value for RSLR within a given timeframe.

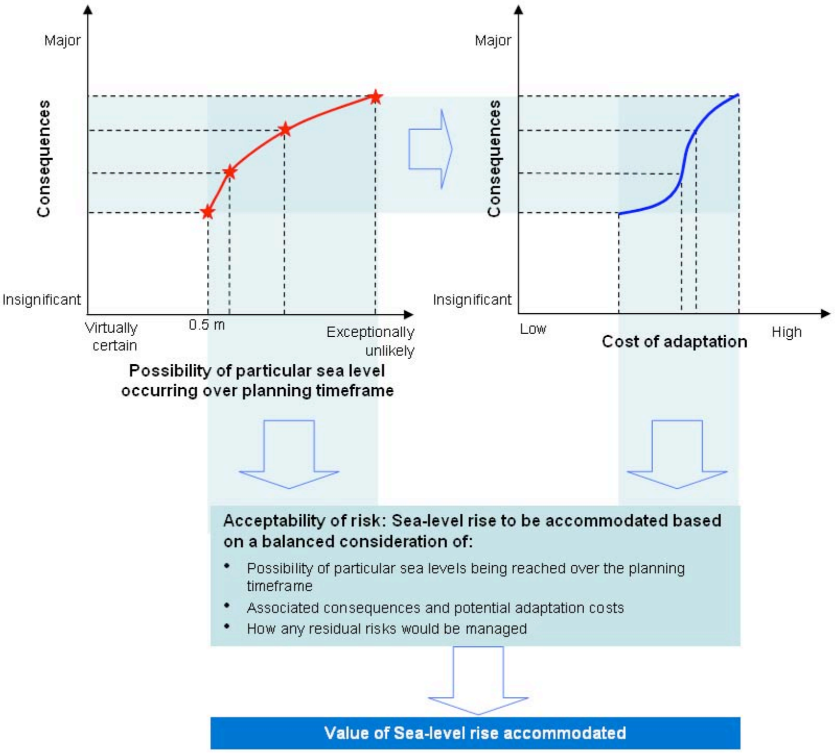

Figure 1. Conceptual representation of deciding on and accommodating sea-level rise based on an understanding and balanced consideration between the possibility of a particular sea-level rise occurring, the potential consequences and associated adaptation costs, and the potential residual risks associated with the accommodated sea-level rise being exceeded.

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Pathways and Impacts of Southern Ocean Currents on Antarctic Icesheet Melting in Response to Global Warming

Frank Colberg[1] and Nathaniel L. Bindoff[1,2]

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Recent direct observations show sea level to be rising at a rate of 3.5 mm yr^{-1}. Over the period 1993-2003 this sea level rise is significantly higher than projected by IPCC climate models and a growing fraction of the overall sea level rise comes from the fresh water input from the melting of the Greenland and Antarctic ice sheets. Recent estimates suggest an accelerating mass loss from the West Antarctic Icesheet, which is thought to manifest itself as a freshening signal in the Antarctic Bottom Water and Antarctic surface waters.

Current coupled-ocean-atmosphere models under-estimate the amount of freshening in the Southern Ocean because they do not include the physics of interaction between the melt of the ice shelves and the ocean and the realistic representation of the ocean cavity beneath the ice shelves

We present results from high resolution ocean model simulations encompassing the whole of Antarctica taking into account ocean cavity and iceshelf interaction. Simulations are run under present day climate conditions and are then compared with simulations forced with the projected atmospheric state as projected by the IPCC A2 emissions scenario in 2100. Model results and diagnosed analyses of total and regional distribution of the melt-rates of the Antarctic icesheet are discussed and compared to observational data such as GRACE gravity fields. The model's capability to adequately represent the mean state of the Southern Ocean is also shown. The distribution of melt from change experiments shows patterns that are broadly consistent with the observed mass changes in the Antarctic ice shelves, and in the circulation pathways of the warm CDW across the shelf break. The wind only, and all forcing experiments have distinctly different characteristics that distinguish the roles of wind driven dynamics in enhancing the melt of the ice shelves within the cavity, and buoyancy driven forcing that also enhance the new melt-rates and distribution of the melt around Antarctica.

SeaRISE: A Community Effort to Determine "How Bad Could Sea-Level Rise Get"?

Robert Bindschadler

NASA and University of Maryland Baltimore Country, USA

Acknowledging the observations of rapid ice-sheet changes, the IPCC-AR4 stated that the "…understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise." Through workshops and conversations, a coordinated effort, named SeaRISE (Sea-level Response to Ice Sheet Evolution), has emerged that seeks to address this weakness in ice sheet models on a schedule to inform the next IPCC Assessment Report. SeaRISE's goal is to provide quantitative, upper bound estimates of ice sheet contributions to sea level for the 21st and 22nd century. Confidence in these estimates will be gained by applying many independent models to a common set of climate and boundary condition scenarios to reduce unrealistic characteristics of any single model from affecting the predictions.

The first experiments are intentionally extreme in their physical realism to help determine the upper bound of possible future ice sheet response. Subsequent experiments representing more likely scenarios will then be run to help lower the upper bound. All models will quantify their calculated ice sheet responses relative to a control run of the same model generated either by holding modern climate fixed in the future or by using AR4 predictions of future climate. This "normalization" process will help minimize unrealistic aspects of any single model and attempt to further isolate the impact of the difference in forcing between the experiment and the control runs.

SeaRISE includes regional models as well as whole ice sheet models. The interactions are expected to be two-way: regional models will be used to help provide more reasonable forcings for selected whole ice sheet model experiments and whole ice sheet models will be used to define boundary fields that will enable regional models to refine the predicted responses of particularly dynamic areas. Another anticipated benefit is that the results of this effort will help inform the implementation of dynamic land ice into the fully coupled Community Climate System Model (CCSM).

Past and Future Ice Sheet Feedbacks with Climate

Jason Box

Ohio State University, USA

In this work, the various known ice sheet feedbacks with climate and the ocean are reviewed to better understand their importance and interplay. Feedbacks considered include: ice-albedo; elevation-temperature; elevation-precipitation; water vapor-precipitation; storm-baroclinicity; meltwater-flow speed; melt season duration-flow speed; cloud radiation-melt; marine terminating glacier thickness-flow speed; etc. The work aims to tabulate and rank the importance and understand the interplay of the various feedbacks. A modeling framework is suggested to rank and evaluate the importance of these feedbacks individually and collectively. Past Greenland ice sheet mass balance reconstructions are used to inform future projections made using IPCC model output.

Sea Level Scenario Development and Impact Assessment in Vietnam

Vu Thanh Ca

Research Institute for the Management of Seas and Islands, Vietnam Administration of Seas and Islands, Vietnam

In Vietnam, the emission scenarios selected for climate change (CC) and sea level rise (SLR) scenario development are low emission scenario (scenario B1), average emission scenario (scenario B2) and average of the high emission scenarios (scenario A2). Based on the adopted emission scenarios, numerical models were employed to develop climate change and sea level rise scenarios. Results of the calculation show that the sea level rise for low emission scenario (B1) is 28cm by 2050 and 65cm by 2100; the sea level rise for average emission scenario (B2) is 30cm by 2050 and 75cm by 2100; and the sea level rise for average high emission scenario (A1FI) is 33cm by 2050 and 100cm by 2100. The sea level rise might be different for different locations along the coast. However, this difference will be evaluated in the future re-assessment of SLR scenarios. Together with SLR, distribution of water temperature in the Vietnamese seas for different CC and SLR scenarios is also evaluated.

The sea levels used for impact assessment of SLR at different locations along the coast of Vietnam are calculated based on SLR scenarios in combination with extreme sea level due to maximum typhoon with occurring frequency of 2%.

Sea Level Budget Over the Past Few Decades and Recent Years: A Review

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In this presentation, we first discuss observations of sea level rise and associated regional variability for 20th century and satellite altimetry era (since the early 1990s). We next discuss most recent progress made in quantifying the processes causing sea level change on time scales ranging from years to decades, i.e., thermal expansion of the oceans, land ice mass loss and land water storage change. The IPCC 4th Assessment Report (IPCC AR4) provided a synthesis of recent progress realized in precisely measuring global mean sea level change as well as understanding the causes of observed sea level rise. For the 1960-2000 time span, the sea level budget could not closed, unlike for the 1993-2003 decade –for which various types of remote sensing and in situ observations are available-. Over this decade, IPCC AR4 estimated that ocean thermal expansion contributed by ~50% to observed global mean sea level rise, the remaining 50% being mostly due to land ice shrinking (with the largest contribution from glacier melting). New studies published since the IPCC AR4 have revisited the sea level budget for the past 4 decades and have shown that the ocean contribution had been underestimated, leading to better agreement between observed sea level rise and climate contributions. Other post-AR4 studies have concentrated on the sea level budget since 2003, a period where ocean thermal expansion can be estimated using newly deployed Argo profiling floats. These observations have shown that ocean thermal expansion has increased less rapidly than during the previous decade, although estimates by various groups are much scattered. Besides, the numerous recent publications on the mass balance of the ice sheets all report accelerated ice mass loss from some coastal regions of Greenland and West Antarctica, so that sea level continues to rise at almost the same rate as during the previous decade. Corresponding increase in ocean mass can also be directly estimated using space gravimetry data from GRACE. Although the GRACE data are contaminated by the (still uncertain) solid Earth response to last deglaciation (i.e., Glacial Isostatic Adjustment), inferred ocean mass increase appears in agreement with most recent estimates of the ice sheets and glacier mass loss. On average over the altimetry era, the sum of climate-related contributions is only slightly less than altimetry-based sea level rise (of 3.3 +/- 0.4 mm/yr), with ~ 30% of the observed rate of rise being due to ocean thermal expansion and ~ 55% resulting from land ice melt. Recent change in land water storage contributes little to this budget. However, intensive dam building during the second half of the 20th Century may have prevented sea level to rise by a non negligible amount.

Effects of Land Waters on Sea Level

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On decadal to multidecadal time scale, thermal expansion of sea waters and land ice loss are the main contributors to sea level variations (Bindoff et al., 2007). However, modification of the terrestrial water cycle due to climate variability and direct anthropogenic forcing may also affect sea level (Milly et al., 2010). While in the recent years, thermal expansion and land ice melt were the object of numerous investigations (see Bindoff et al., 2007 and Cazenave and Llovel, 2010 for reviews), the terrestrial water contribution to sea level has been less studied (Milly et al., 2010). For the past decades, variations in land water storage caused by climate change and variability cannot be directly estimated from observations because these are almost inexistent at global continental scale. However global hydrological models developed for atmospheric and climatic studies can be used for estimating total water storage (Milly et al., 2010). Model-based studies (Ngo-Duc et al., 2005, Milly et al., 2003) estimated the terrestrial water storage contribution to sea level over the past few decades and found no climatic long-term trend but large interannual/decadal fluctuations, of several millimetres amplitude when translated in sea level equivalent. Direct human intervention on land water storage and induced sea level changes have been estimated in several studies (Milly et al., 2010). The largest contributions come from ground water pumping (either for agriculture, industrial and domestic use) and artificial reservoir filling. Although detailed information is lacking and estimates vary significantly between authors, ground water depletion may have contributed to past decades sea level rise by ~ +0.3 mm/yr while water impoundment behind dams has led to sea level drop (~ -0.5 mm/yr) over the second half of the past century (Chao et al., 2008).

For the recent years (since mid-2002), terrestrial water storage change can be directly estimated from observations of the GRACE space gravimetry mission. In two previous studies (Ramillien et al., 2008, Llovel et al., 2010), we estimated the water volume trend in the 33 largest river basins worldwide using GRACE, and found small net water volume change globally since 2003, with a +/- 0.2 mm/yr sea level contribution. In this poster, we revisit and update total water storage trend over the GRACE period (and corresponding contribution to sea level) using different GRACE products. We further analyse the interannual variability of total land water storage, and investigate its contribution to mean sea level variability. We consider three different periods that, each, depend on data availability: (Bindoff et al., 2007) GRACE era (2003-2009), (Milly et al., 2010) 1993-2003 and (Cazenave and Llovel, 2010) 1955-1995. Before the GRACE era, we use outputs from the ISBA-TRIP global hydrological model (developed at CNRM/MeteoFrance). For each time span, we compare observed (detrended, annual cycle removed) mean sea level and total water storage (sum of the 33 largest river basins). Figure1 compares interannual variability in sea level (corrected for steric effects, trend and annual cycle removed) with GRACE-based and ISBA-TRIP-based water storage change (two GRACE products are considered). We find that, on interannual time scale, land water storage significantly contributes to global mean sea level variability. Tropical river basins, in particular the Amazon basin, are the dominant contributors. For the other periods (1993-2003 and 1955-1995), comparisons based on ISBA-TRIP also confirm the significant contribution of land waters to interannual mean sea level. The results point out for a dominant ENSO signature, with drier than normal conditions during ENSO events in tropical basins leading to negative water storage, hence positive sea level anomalies.

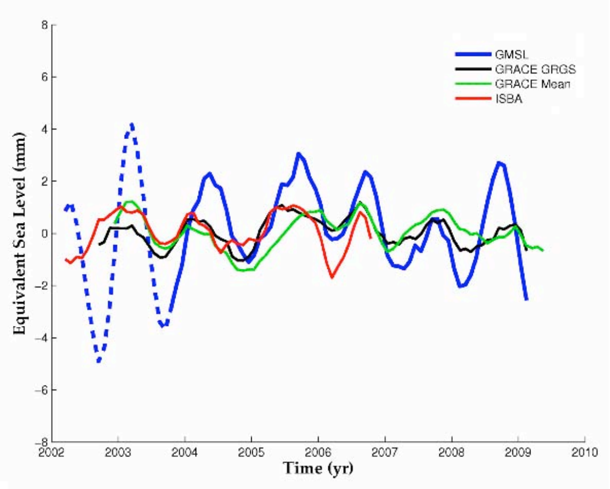

Figure 1. Interannual variability over 2003-2009 of altimetry-based global mean sea level corrected for thermal expansion (blue curve) and terrestrial water storage -expressed in equivalent sea level- (red curve: data from the ISBA-TRIP hydrological model; green curve: data from GRACE –mean CSR/GFZ/JPL products-; black curve: data from GRACE; GRGS products). The time series are detrended and the seasonal cycle is removed.

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Climate Induced Changes on Water Resources: A Need for Quantifying Risks and Reducing Uncertainties

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According to current climate projections, Mediterranean countries are at high risk to changes in the hydrological budget and extremes. These changes are expected to have strong impacts on the management of water resources, agricultural productivity and drinking water supply.

The Chiba river basin, located in the North-East of Tunisia; is delimited by mountains in the West, Two catchments in the North and North-East, and another in the South-West and by the Mediterranean sea in the East. Its landscapes are already experiencing and expecting a broad range of natural and man-made threats to water security, including severe droughts, extreme flooding, salinization of coastal aquifers and degradation of fertile soils.

On the other hand, little knowledge is available to quantify climate induced changes, due to a lack of suitable and effective hydrological monitoring and modeling systems. Projections of future hydrological change, based on climate model results and hydrological modeling schemes, are very uncertain and poorly validated. Further, the conditions required to develop and implement appropriate adaptation strategies for basin scale are lacking. If adaptation initiatives are proposed at all, they are rarely based on a multi-disciplinary assessment covering both natural and associated social and economic local changes.

It is within the Seventh Framework Programme for Research and Technological Development, funded by the European commission, that a collaborative Research project, entitled CLIMB: ”Climate Induced Changes on the Hydrology of Mediterranean Basins”, was launched in January 2010 to study several study sites including the Chiba Basin. The Center for Water Research and Technologies in Tunisia, aims to employ and integrate the CLIMB new conceptual framework to the Tunisian study site based on advanced geophysical field monitoring techniques for the artificial water recharge pilot site, remote sensing analyses and retrievals, integrated hydrologic modeling and assessment climate change scenarios extracted from models auditing and downscaling.

Improvements will be communicated to stakeholders and decision makers in a transparent, easy-to-understand form, enabling them to utilize the new findings in regional water resource and agricultural management initiatives as well as in the design of mechanisms to reduce potential for conflicts.

Sea Level Rising Around the Korean Peninsula

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Due to the global warming, the global sea level is rising and this trend threatens coastal regions of Far East Asia, one of the most populated areas. Therefore, it is necessary to understand the sea level rising in these areas. In the present study, we investigated the long-term changes of sea level around the Korean Peninsula during 1982-2001 period (see the study area in Figure 1), adopting CSIRO's 1° × 1° gridded Sea Surface Height (SSH) data (Church et al., 2004) and tide gauge data of Korea Hydrographic and Oceanographic Administration (http://http://www.khoa.go.kr/). In addition, we examined the effect of ocean heat status on the sea level variation using 1° × 1° gridded NOAA OI-SST data and NODC Ocean Heat Content (OHC) data integrated 0-700 m depth.

By using simple linear regression method, change rate of sea level in each grid is calculated. In general, sea level in the most regions reveals positive trends during 1982-2001 periods. In particular, sea level change near the southern Yellow Sea and East/Japan Sea is large, showing the rate more than 3.0 mm yr^{-1}. The spatially averaged SST and OHC in the sea around Korean Peninsula reveal similar temporal variation with SSH. The linear correlation coefficients between SSH and SST (OHC) are 0.61 (0.62), 0.68 (0.55), and 0.72 (0.5) in the Yellow Sea, northern East China Sea and East/Japan Sea, respectively.

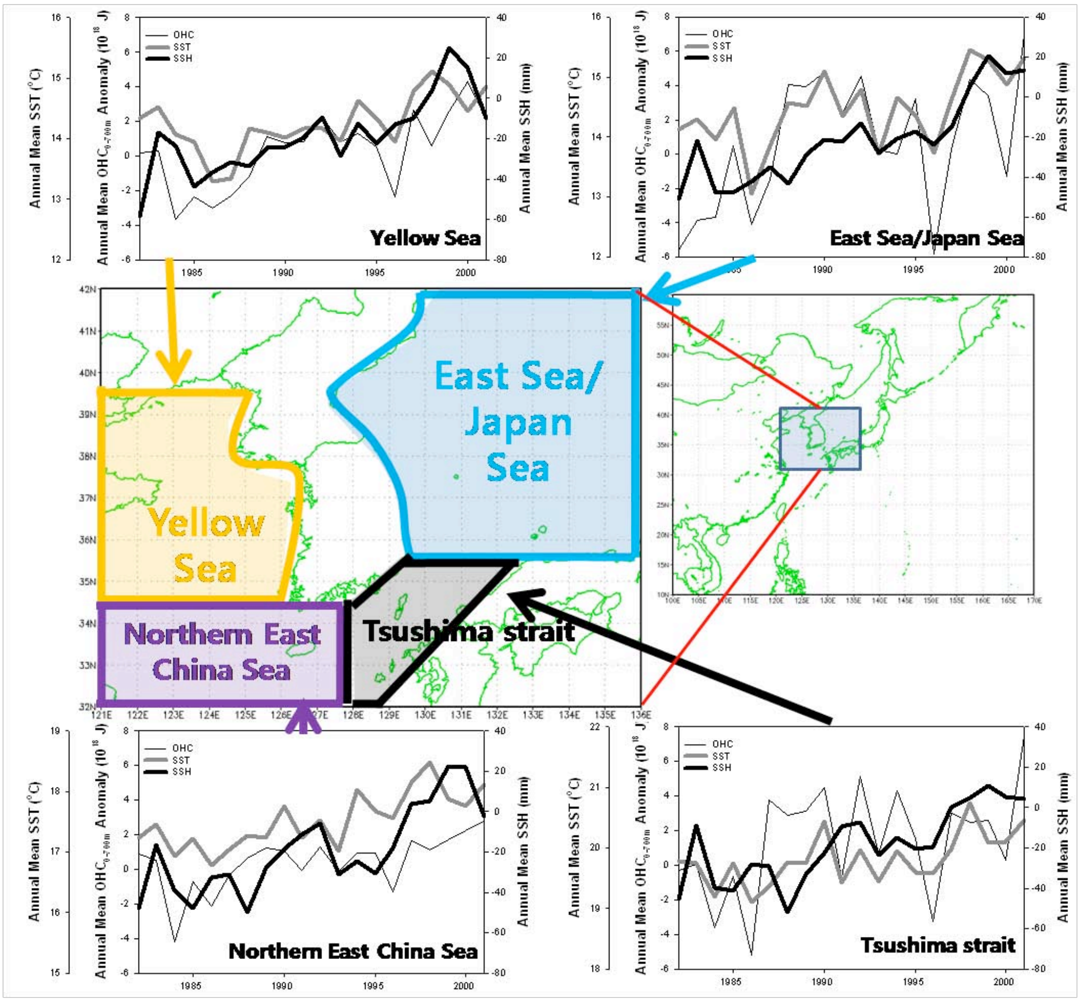

Figure 1. Study area. Small boxes indicate interannual variations of sea level (thick black line), SST (gray line), and Ocean Heat Content (OHC; thin black line) in the Yellow Sea, northern East China Sea, and East/Japan Sea.

To examine the sea level changes along the coastal line of Korean Peninsula, linear trends at 14 stations are estimated using tide gauge data. The results show the sea level along the coast generally increases during last 20 years; the change rates are 3.19 mm yr^{-1}, 2.50 mm yr^{-1}, and 4.67 mm yr^{-1} along coasts adjacent to the Yellow Sea, the northern East China Sea, and the East/Japan Sea, respectively. Sea level rising rate derived from tide gauge data is about 1.0-2.0 mm yr^{-1} smaller than that from SSH data. In particular, the difference is relatively large in the Yellow Sea and northern East China Sea, where the tidal range is large. The difference might be caused by the property of SSH data; according to Youn et al., (2000), the TOPEX/Poseidon satellite altimetric data, applied in the reconstructed SSH data, could contain some error in the marginal sea where tidal range is large. The present study shows the evidence of sea level rising in the marginal seas of north Pacific Ocean (i.e., sea around the Korean peninsula), using globally reconstructed SSH data and tide gauge data at 14 stations. Also, it is shown that the sea level change is correlated with the long-term change of ocean thermal expansion.

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Global and Regional Sea Level Rise Resulting from Changes in the Greenland Ice Sheet Modelled with a Coupled High Resolution RCM and Ice Sheet Model

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For reliable global and regional sea level prediction in the future it is necessary to estimate the contribution of the Greenland Ice Sheet. Modelling efforts have been limited by, among other things, the low resolution of climate forcing, poorly known basal boundary conditions for the ice sheet, and lack of representation of fast flowing ice streams. We address these limitations by building a model system consisting of coupled high resolution regional climate model (HIRHAM5), and Parallel Ice Sheet Model (PISM), which simulates spatially and temporally varying ice stream by use of the shallow shelf approximation as a 'sliding law' for the shallow ice approximation. The surface mass balance that drives the ice sheet model is calculated within HIRHAM5 to take advantage of a newly implemented energy balance model. The surface scheme of the climate model has also been upgraded over glaciers and ice sheets to account for important processes including snow transformation, melt, refreezing and superimposed ice formation. The resultant model system shows a substantial improvement over HIRHAM4 in characterizing the mass balance and dynamics of the Greenland Ice Sheet and gives us confidence in applying it to future climate scenarios. This model system will provide input for numerical predictions of gravitationally consistent pattern of sea-level change that would result from the predicted volume changes of the Greenland Ice Sheet. When appropriately used in connection with regional storm surge and wave modeling, such non-uniform sea-level rise pattern will assist in providing a better constrained regional sea-level rise pattern will assist in providing a better constrained regional sea-level rise projections for example for the area around Denmark and Greenland.

Past and Present Sea-Level Changes: Key Conclusions and the Way Forward

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Significant progress has been made in understanding global averaged sea-level rise for the period since 1961, for the satellite altimeter period since 1993 and for the GRACE period since 2003. Ocean thermal expansion, glaciers and ice cap contributions and a growing contribution from the ice sheets are the largest contribution to closure of the sea-level budget over each of these periods. It also important to consider the terrestrial storage of water. Previous studies have shown the rate of observed sea-level rise has been close to (or above) the upper end of the model simulations. With the improved closure of the sea-level budget, the observational components should be used to more critically test the models and to constrain future projections, including the semi-empirical models.

To date there has not been the same progress in determining a robust regional distribution of sea-level rise, or of the factors that control this distribution, as there has been for the global averaged rise. Future studies, need to better understand this regional distribution, including an allowance for the changes in the gravitational field associated with the changing mass distribution on the Earth and local land motions, including in deltaic regions and major coastal cities.

Extreme sea-level events have most impact on society. Globally, these seem to be changing primarily in response to changes in local mean sea level. Understanding of the interaction between global mean sea-level change, large-scale interannual variability and local storm surges, including wave-driven impacts (21st century wave changes have not received enough attention) need to be improved.

Balancing the Global Sea Level Budget Over the Last Half Century

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Understanding the energy stored in the ocean is critical to estimating consistent energy and sea-level budgets and to constraining future projections. The goal of closing the 20th century sea-level budget has been elusive with the sum of contributions consistently being less than the observed rise. There have also been several recent failures to adequately resolve the Earth's energy budget. Here we combine updated and new estimates of the observed sea-level rise and all of the major contributions to the sea-level and energy budgets. We find the average observed rise from 1961 to the end of 2008 (1.8 ± 0.2 mm yr^{-1}) is in good agreement with the sum of contributions (1.8 ± 0.2 mm yr^{-1}) and increases with time in both the observations and sum of contributions. The largest contributions coming from the melting of glaciers and ice caps (0.7 mm yr^{-1}, 40% of total) and thermal expansion of the ocean (0.7 mm yr^{-1}, 40%) and the Greenland contribution (0.2 mm yr^{-1}, 10%). The Glaciers and Ice Caps and the Greenland Ice Sheet contributions increase through the period but the ocean thermal expansion contribution increases less rapidly. There is a small net terrestrial storage contribution (the difference between two large terms). The implied net Antarctic contribution, estimated as a residual in the sea-level budget, is positive but likely to be small and with a large uncertainty. The heat budget is dominated by ocean heat content (over 90%) and the energy storage increases through to the end of the record, in agreement with continued greenhouse gas forcing of the Earth.

Ice-Shelf Collapse from Subsurface Warming as a Trigger for Heinrich Events

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Episodic iceberg-discharge events from the Hudson Strait Ice Stream (HSIS) of the Laurentide Ice Sheet, referred to as Heinrich events, are commonly attributed to internal ice-sheet instabilities, but their systematic occurrence at the culmination of a large reduction in the Atlantic meridional overturning circulation (AMOC) indicates a climate control. We report Mg/Ca data on benthic foraminifera from an intermediate-depth site in the northwest Atlantic and results from a climate-model simulation that reveal basin-wide subsurface warming at the same time as large reductions in the AMOC, with temperature increasing by ~2oC over a 1-2 kyr interval prior to a Heinrich event. In simulations with an ocean model coupled to a thermodynamically active ice shelf, the increase in subsurface temperature increases basal melt rate under an ice shelf fronting the HSIS by a factor of ~6. By analogy with recent observations in Antarctica, the resulting ice-shelf loss and attendant HSIS acceleration would produce a Heinrich event.

Greenland Ice Cores Tell Tales on the Extent of the Greenland Ice Sheet During the Warm Climate Eemian Period 120,000 Years BP

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All the ice cores drilled though the Greenland ice sheets have been analyzed and the results show that all the ice cores contain ice from the previous warm Eemian period near the base. Is it thus clear that the Greenland Ice Sheet did exist for 120,000 years ago in the previous warm period where it was 5°C warmer over Greenland.

The difference between the Eemian and the Holocene stable oxygen isotope values have been combined with an ice sheet flow model constrained by the ice core results and internal radio echo sounding layers to estimate the volume of the Greenland Ice Sheet 120,000 years ago.

The results show that South Greenland has not been ice free during the Eemian period and that the sea level contribution from the Greenland Ice Sheet has been 1-2m.

Global and Regional Thermosteric Sea-Level: Time Series, Linear Trends, Geographical Patterns and Comparison with CMIP3 Climate Model Simulations

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Thermosteric sea level is a major factor contributing (about 40%) to the observed global mean sea-level rise in the latter half of the 20th century (Domingues et al., 2008; Church et al., 2010), and is likely to continue to be one of the largest contributing factors in the 21st century (Gregory et al., 2001). At global scale, the observed mean thermosteric sea-level rise is explained by the expansion in ocean volume due to a net increase in ocean heat content over the past 50 years. At regional level, geographical patterns are produced in response to dynamical processes, with some areas experiencing variations above and others below the observed global mean thermosteric sea-level rise (e.g., Bindoff et al., 2007; Church et al., 2008). Coupled Model *Intercomparison Project* (CMIP3) model simulations show a continuous increase in global mean thermosteric sea level; however, some simulations tend to overestimate and others to underestimate the observed rise in the upper 700 m of the oceans during 1960-2000 (Domingues et al., 2008). Model simulations are also known to have large discrepancies in regional patterns and model-data comparisons are required to help reduce these uncertainties and, thus, to increase confidence in model projections at regional scales (e.g., Gregory et al., 2001; Meehl et al.,2007; Milne et al., 2009) – where ultimately the effects of sea-level rise will impact our society. Here, we update the 0-700 m depth-integrated time series of global mean thermosteric sea level in Domingues et al. (2008) for the 1960-2008 period (e.g., 5 years longer) and examine the contribution of individual ocean basins to global trends and describe their regional patterns. We also compare estimates from other observational analyses (Levitus et al., 2009; Ishii and Kimoto, 2009) and CMIP3 climate model simulations with our results. Our updated thermosteric sea level estimates were formed as described in Domingues et al. (2008), using the same reduced-space interpolation technique (Kaplan et al., 2000), historical data set (Ingleby and Huddleston, 2007) and time-dependent fall-rate correction (Wijffels et al., 2008) to minimise systematic biases in eXpendable BathyThermographs (XBTs). From 2000 to 2008, the updated time series include our own version of the modern Argo data set (Gould et al., 2004), carefully quality-controlled and corrected for pressure biases recently described in Barker et al. (2010). Overall, our thermosteric sea level estimates continue to indicate a global rise of about 0.51 ± 0.09 mm yr^{-1} for 1961-2008; 0.62 ± 0.12 mm yr^{-1} for 1970-2008; and 0.85 ± 0.48 mm yr^{-1} for 1993-2008.

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Mass Loss of Greenland and Antarctica from GRACE and ICESat

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The GRACE satellites measure the mass loss of the major ice sheets, and thus give direct estimates of the sea level rise components. ICESat measures height changes, and identifies more precise the regions of the ice sheets showing the major changes. Together the two satellite systems show a consistent picture of ice mass loss in marginal zones of the ice sheets, and increasing trends in some central regions. We estimate use a direct mass inversion method the overall mass balance of Greenland and Antarctica at around –205 and –100 GT/year, respectively, corresponding to .08 mm/year global sea level rise. Large uncertainties are due to glacial isostatic adjustment (GIA), which for Antarctica contribute more than 1/3 of the measured change signal. Differences of results based on different GIA modes, as well as different GRACE processing centers, thus add substantial uncertainty to current mass loss rate estimates. For Antarctica, mass loss is largest in the Thwaites-Pine Island Glacier regions of West Antarctica, and in the northern Antarctic Peninsula; in Greenland changes are largest in SE Greenland, with mass loss trends currently increasing along the NW margin, consistent with the observed increase in flow speeds of major outlet glaciers.

Surface Mass Balance of Antarctic Ice Sheet

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Slow changes in Antarctic mass balance and flow are complex and relate to centennial to millennial time scales, making attribution to causes difficult. XX century Antarctica's contribution to sea level change has been hampered by poor knowledge of surface mass balance or snow accumulation. Several processes act on snow accumulation on the surface of an ice sheet and introduce large uncertainties in past, present, and future ice sheet mass balance. Solid atmospheric precipitation (snowfall and diamond dust/clear sky precipitation) is deposited at the surface of the Antarctic ice sheets. Wind erosion, wind redistribution, sublimation, melting and other processes during or after the precipitation event lead to a deposition at the surface which is spatially less homogeneous than the original precipitation.

Surface mass balance of Antarctica is about 2200 Gt yr^{-1}, but until recent advances, the uncertainty in surface mass balance estimates is more than 10% (equivalent to nearly 0.6 mm yr^{-1} of sea level rise) and is greater than any other components of ice sheet mass balance. Modern altimetry and gravimetry technologies are now strongly improving detection possibilities at shorter (decadal) time scales. However, several processes that act on snow accumulation on Antarctic Ice Sheet introduce significant uncertainty into the cross-comparison of rates of change in ice-surface elevation (e.g., from satellite altimetry measurements), with in situ measurements of snow accumulation, and with the precipitation fields that are output from climate models and re-analyses.

Global climate models suggest that Antarctic snowfall should increase in a warming climate, mainly due to the greater moisture-holding capacity of the warmer atmosphere. In the troposphere above the surface of Antarctica, there has been a fairly strong winter warming since the early 1970s, the season in which much of Antarctica receives its maximum snowfall. There are evidence of a warming and freshening trend in the ocean waters of the Southern Ocean and sea ice extent reduction during 1950s and 1960s. Research in recent decades from snow accumulation (firn core coupled with atmospheric reanalysis model) over the continent indicates that there are statistically insignificant or slightly negative snow accumulation changes over Antarctica since the 50s and probably since XIX century, inferring that sea level rise has not been mitigated by Antarctic snow accumulation changes.

Slope and coastal areas of the Antarctic Ice Sheet are known as the area of our planet with the highest winds and blowing snow. Strong katabatic winds blow throughout the year, and a large but unknown fraction of the snow that falls on the ice sheet is continuously exported to the atmosphere and the Southern Ocean.

In katabatic wind converge area, blowing snow transportation occurs for 80% of the time, and 20% of time, the flux is $>10^{-2}$ kg m^{-2} s^{-1} with particle density increasing with height (up to 200 m from the ice sheet surface). Cumulative snow transportation is 4 orders of magnitude higher than snow precipitation at the site. Increase in annual wind speed and transportation allow a reduction of the same order of observed annual snow accumulation.

Extensive presence of ablation surface (blue ice and wind crust) in katabatic wind convergence area and in its downwind coastal area suggest that the combined processes of blowing snow sublimation and snow transport remove up to 50% of the precipitation at regional scale. A combination of remote sensing and field data allow identifying regions of wind crust and blue ice surface. Wind crust and blue ice areas are characterised by surface mass balance from slightly positive or nil (10 kg m^{-2} yr^{-1} > wind crust > -50 kg m^{-2} yr^{-1}) to strong negative (-50 kg m^{-2} yr^{-1} > blue ice area > -500 kg m^{-2} yr^{-1}). Wind crust cover approximately 20% and blue ice about 2% of East Antarctic Ice Sheet surface. Wind crust and blue ice are presented in the slope convergence, confluence area and in coastal. This shows that transported snow is primarily exported directly in the atmosphere (blowing sublimation) and secondarily in the ocean. Snow depositional processes are very rare and negligible in the surface mass balance estimation. Blowing snow ablation represents a major negative effect on the snow accumulation, and they are not sufficiently taken into account in studies of present and future surface mass balance. The observed wind-driven ablation explains the inconsistency between atmospheric model precipitation and measured snow accumulation value.

Since these areas are much lower in accumulation than current compilations of surface mass balance based on interpolation of measurements or climate-model determinations of net accumulation, the presence of extensive wind crust implies that surface mass balance is overestimated at present and suggest that the rate of contribution of Antarctic Ice Sheet to sea level rise, using component approach, is underestimated. Information about snow surface processes is essential not only for the input component term of the mass balance but also for interpreting surface elevation change and gravity anomaly signals, and for improving climate and meteorological models.

To be able to predict future trends in ice sheet mass balance our models need to be able to reliably reproduce present-day and recent past patterns (from years to millennium scales) of surface mass balance. Future scenarios from global climate models suggest that Antarctic snow precipitation should increase in a warming climate, mainly due to the greater moisture-holding capacity of the warmer atmosphere, but this could be offsetting by enhanced loss due to wind blowing ablation.

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Changes in Ocean Properties Influencing Sea Level: Observations, Modelling and Uncertainties

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When water warms, it expands. Roughly speaking, warming the top 1000 meters of the ocean by 0.1°C will result in 2 to 3 cm of thermosteric sea level rise. In analyses of recent global sea level rise, thermosteric effects are responsible for 40-50% of overall sea level rise. (Formally, the exact response of global sea level to changing ocean properties depends on both salinity and temperature, and the equation of state is non-linear, but salinity effects are relatively minor corrections compared with other uncertainties in the sea-level budget.) Recent research on thermosteric sea level rise has highlighted several key issues that did not feature in the 2007 IPCC Working Group I report. First, a series of recent studies has identified and addressed problems with several in situ data used to estimate thermosteric sea level rise: fall rates for expendable bathythermographs (XBTs) have been corrected; erroneous Argo float profiles have been flagged; and efforts have continued to evaluate other historic data types. Second, because of the paucity of deep ocean observations and because the deep ocean is usually thought to be well insulated from change at the ocean surface, most studies of thermosteric sea level have concentrated on changes in the top 1000 or 2000 meters of the ocean. However, recent analyses of deep ocean observations indicate clear evidence for measurable warming in the deep ocean, suggesting the possibility that the deep ocean could contribute to thermosteric sea level rise. Finally, a number of studies have found that sea level rise estimates are sensitive to the methods used to "infill" geographic and temporal gaps in historic data records. Advances since the 2007 IPCC report have generally led to sea level rise estimates that appear more robust and more consistent with expected climate responses to volcanic eruptions.

Warming in the Southern Ocean: Heat Content Changes and Meridional Migration of the Antarctic Circumpolar Current

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Long-term temperature trends in the Southern Ocean indicate that the region has warmed from the surface to at least 1000 m depth over the past 50 years. The observed warming trend appears consistent with a multi-decadal scale poleward migration of the Antarctic Circumpolar Current (ACC), possibly linked to a long-term shift in the Southern Annular Mode. However, other studies have hypothesized that changes in eddy variability may be important in explaining the major changes and their role in global climate processes. These trends have the potential to influence sea level, both through thermal expansion of the ocean and also by delivering heat to the Antarctic continent, contributing to basal melting of grounded ice. Since historic in situ hydrographic data are sparse, definitive assessments of the actual trends and mechanisms governing them have proved difficult. Moreover, strong annual cycles in ocean heat content complicate any analysis. Satellite data from microwave sea surface temperature sensors and altimetric sea surface height offer some promise for evaluating the meridional migrations of the ACC, and its sensitivity to changes in the Southern Annular Mode. Results are sensitive to the method used to track long-term changes in ACC frontal positions, but generally indicate that the ACC responds clearly to the Southern Annular Mode on timescales of 3 months or less. Processes governing the long-term trends in the position of the ACC are less clear, and changes in eddy heat transport may prove to be more important on longer time scales. The long-term impact of climate change in the ACC on basal ice melting remains an area of research.

Future Sea-Level Changes: Key Conclusions and the Way Forward

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Change in sea level is an important consequence of climate change owing to its potentially widespread, rapid and long-term impact on society and ecosystems. Reliable projections of global, regional and extreme sea level change are therefore needed by policy-makers and planners. It is a scientific challenge to provide such projections and evaluate their uncertainty on the basis of available information from models and observations. Evidence of past sea-level variability and change should be employed in the assessment of the systematic uncertainty of model-based projections. For projecting the contribution due to density and circulation change, we can use global climate models, evaluated and constrained by comparison with past observed changes; there is a large uncertainty regarding the pattern of regional change, on which models do not agree. Models are less well developed for the contributions from land ice and data for evaluation is less readily available, especially for rapid dynamical changes in ice-sheets. Mean sea-level change is the dominant influence on changes in local extreme sea levels, but there is further uncertainty associated with predictions of regional climate change.

The Current Contribution to Sea-Level Changes from High Arctic Glaciers and Ice Caps in Svalbard, Norwegian Arctic

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The high Arctic glaciated regions with ~244,000 km^2; Russian Islands (56,000 km^2), Svalbard Arcipelago (36,000 km^2) and Canadian Arctic (152,000 km^2), has about 1/3 of the Earth's glaciers and ice caps. The aim of the International Polar Year project GLACIODYN has been to reduce the uncertainties in Arctic Glaciers and Ice Caps (GIC) contribution to sea level changes. Selected target GICs have been studied in the Arctic.

We have focused on Svalbard glaciers. The largest ice cap is Austfonna (8200 km^2), by far the largest ice cap in Svalbard and one of the largest in the Arctic. For the Austfonna ice cap net surface mass balance shows slightly negative results of –0.1 m/yr water eq. or –0.7 ± 0.2 Gt/yr for the period 2004-2008 (Moholdt et al., 2010). The calving is important and gives 2.5 Gt/yr and stands for 30–40% of the total mass loss, giving an overall loss of –0.4 m/yr (Dowdeswell et al., 2008). However, the elevation change measurements on Austfonna show a thickening in the interior of c. 0.5 m/yr, and an increasing thinning closer to the coast of 1–2 m/yr, indicating a large dynamic instability.

The general picture from Svalbard glaciers is retreating glacier fronts with thinning in lower elevation and a thickening in higher elevations. However, the frequent surge-type dynamics of Svalbard glaciers must be considered in geometry change studies. Flux calculations show the importance of the dynamics for many different glaciers. Mass loss due to calving from the whole archipelago is estimated to 6.8 ± 1.7 Gt/yr or ca. 20% of the overall ablation from Svalbard glaciers (2000–2006) (Blaszczyk et al., 2009).

Satellite altimetry from ICESat (2003–2007) have been compared to older topographic maps and digital elevation models (1965–1990) to calculate long-term elevation changes of glaciers on the Svalbard Archipelago. Geodetic balances are related to latitude and to the dynamical behavior of the glacier, for example, whether it has surged or is in a quiescent phase. The overall mass loss from Svalbard glaciers over the past 40 years for Svalbard is about –13 ± 0.6 Gt/yr, or a specific net balance $b_n = -0.36 \pm 0.03$ m/yr which is in SLE = 0.036 ± 0.02 mm/yr (Nuth et al., 2010; Moholdt et al., 2010). This is in good agreement with in situ mass balance measurements, but significant more than former estimates for the 30 year period before 2000 of about –5 ± 1 Gt/yr (Hagen et al., 2003). Geodetic measurements suggest that the rate of volume loss from low-lying glaciers close to the west coast has increased by up to a factor of four since the early 1960s (Kohler et al., 2007).

The current data from the high Arctic (Canada, Svalbard, Russian Arctic) indicate an increasing negative mass balance (Abdalati et al., 2004; Koerner, 2005; Burgess et al., 2005; Glazovsky and Macheret, 2006; Mair et al., 2005, 2009). ICESat data indicate a more negative mass balance for the period 2003–2008 than for the earlier decades also in the Russian Islands (Moholdt et al., in prep.). The overall high Arctic net mass balance over the last 10–20 years is then: $B_n = -38 \pm 7$ Gt/yr or $b_n = -0.15 \pm 0.03$ m/yr which is in SLE = 0.11 ± 0.02 mm/yr. Thus these glaciated regions covering just above 30% of all GICs in the world contribute only about 11% of the current estimated GIC input to global sea level (~1.1 mm/yr, Meier et al., 2007), but have a large potential to higher contribution.

Table 1. Estimates of the current net mass balance of high Arctic glacier regions.

Region	Area 10^3 km^2	B_n Gt/yr	b_n m/yr	SLE
Canadian Arctic	152	–21 to –26	–0.13 to –0.17	0.06 to 0.07
Svalbard	36	–5 to –14	–0.12 to –0.38	0.01 to 0.04
Russian Arctic Islands	56	~ –5	~ –0.1	~0.01
Total High Arctic	244	–31 to –45	–0.13 to –0.18	0.09 to 0.12

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Investigation on Impact of Climate Change to an Increasing of Sea Surface Temperature in Indonesian Waters

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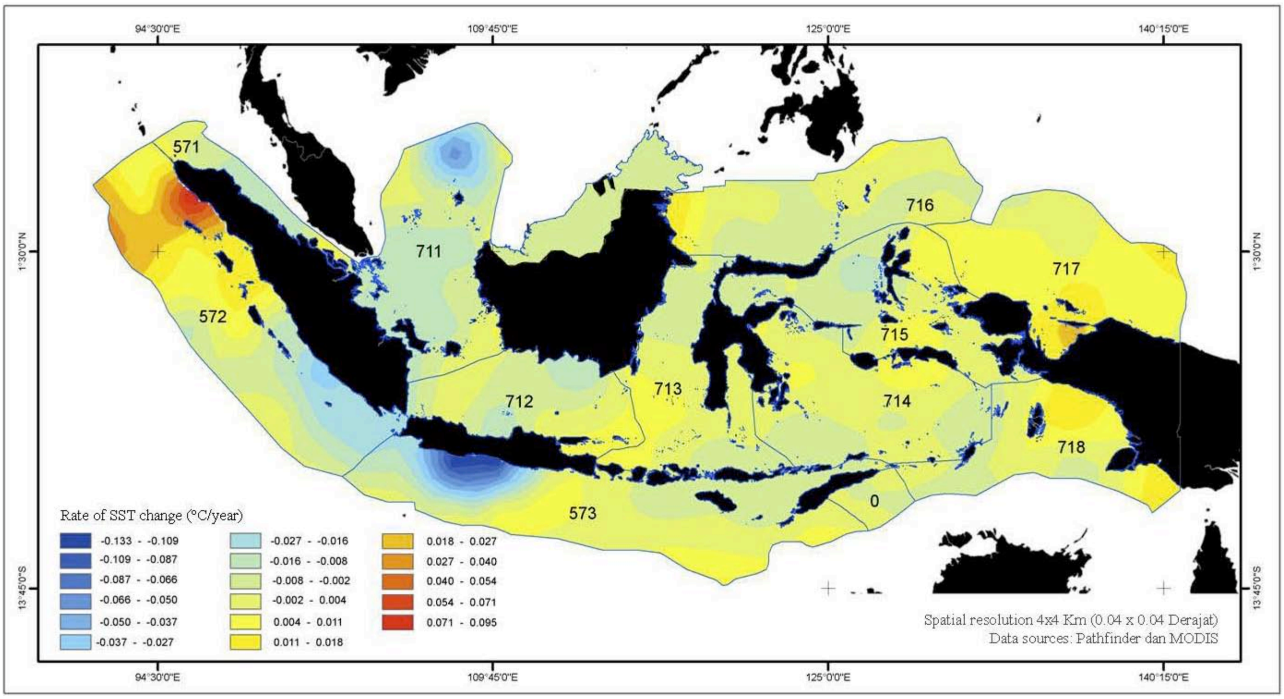
Indonesian water lies in the tropical region with geographic position 6°N to 11°S and 95° to 141°E. Indonesian Throughflow (ITF) from the Pacific Ocean into the Indian Ocean has been considered to give significant impact on water mass circulation and global climate. Tropical water, including Indonesian water, is believed to influence the global atmospheric conditions since it is considered to be the region where events related to climate change develop and also climate affected by El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole. Transfer of warm water from the Pacific Ocean to the Indian Ocean influence the expansion of the warm water distribution in the western Pacific, which is associated with several ENSO events. It is believed that an anomaly in sea surface temperature (SST) gives a significant influence on climate, and then annual variation of the ITF will contribute to the ENSO events.

SST trend and anomaly in the Indonesian water were observed using SST derived from satellite in the period of 1985 to 2008. The rate of change of SST is shown to have a positive trend with an average value of 0.005 °C/year, where the lowest and highest rate of change are –0.133° and 0.095°, respectively. The region of Indonesian water with a positive trend of SST (sea warming) is 58%. SST anomaly, which is a deviation value from the condition of the last 5 years (2003–2008) compared to the previous 18 years (1985–2002), is 0.034 °C/year or six times larger than the rate of change for the last 24 years. The area with positive anomaly is around 97% and that with negative anomaly is 3%, where negative temperature anomaly occurred mainly in upwelling regions.

Impact of SST increase has been identified randomly in Indonesian waters. The following are Indonesian waters zones affected by sea warming; arranged from highest anomaly value and area to the least affected. They are: Cendrawasih Bay, Aru Sea, Arafura Sea, east of Timor Sea, Banda Sea, Makassar Strait, Gulf of Bone, Flores Sea, Bali Sea, Indian Ocean in west of Sumatra, Sunda Strait, Celebes Sea, Gulf of Tomini, Maluku Sea, Halmahera Sea, Ceram Sea, Gulf of Berau, Indian Ocean from south of Java to south of Southeast Nusa Tenggara, Sawu Sea, west of Timor Sea, Java Sea, Malacca Strait, Andaman Sea, Karimata Strait, Natuna Sea and South China Sea.



Water dynamics, for example increase and decrease of SST triggered by an ENSO event occurred unevenly in Indonesian waters. In several areas such as coastal waters of the Indian Ocean in west of Sumatra and south of Java, Java Sea and Makassar Strait have been identified to be strongly impacted. It may give a negative impact on coastal ecosystems such as coral bleaching. These results may have a connection with sea level rise occurrence in Indonesia. Further assessment will focus on an observation and model simulation to predict sea level rise in Indonesia using altimetry satellite in combination with tide gauge dataset from the last two decades. This research project has been funded by Ministry of Research and Technology of Indonesia.

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Ice-Sheet Modelling Work Relevant to WG1 Objectives Being Undertaken at BAS

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BAS ice-sheet modelling work covers both palaeo-work, focussing on the period since the last glacial maximum and interglacials, initialisation and predictions, and more detailed process analyses. We will show examples of these activities in the poster.

Projects funded by Ice2sea cover a theoretical analysis of how to initialise ice-sheets using current information about the ice-sheet state, with applications to Greenland and Antarctica, and a more detailed look at the Antarctic Peninsula. Problems are estimation of the basal or sliding viscosity, and in the Peninsula the basal topography. Work will be based around the methodology proposed by Arthern and Hindmarsh (2003). Ice2sea is also funding participation in the MISMIP-2 round of grounding line intercomparisons.

Work funded by NERC and Past4Future will involve using an ice-sheet model to look at the deglaciation of West Antarctica, especially the data-poor Weddell Sea region, and also to investigate how West Antarctica and Greenland responded to warmer conditions in MIS 5 and 11.

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Ice Sheet – Ocean Interactions and Implications for Melting and Instabilities

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The interaction of the floating periphery of the major ice sheets with ocean waters represents one mechanism by which rapid changes in ice sheet mass balance may occur. Three key processes in central to the understanding of the evolution of ice shelves are: calving flux at the ice front, grounding line migration and mass flux, and basal melting in the sub ice-shelf cavity. Over the past few decades progress, to varying degrees, has been made in observing and modeling each of these processes. In this talk, an overview of the main advances in both observations and models is presented for each process and suggestions for future work are given.

Response of the Polar Ice Sheets on Centennial to Millennial Time Scales from Improved 3-D Whole Ice-Sheet Models

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Our suite of 3-D thermomechanical models of the Greenland and Antarctic ice sheets have been widely used over the last two decades to better assess the contribution of the polar ice sheets to global sea-level change. In predictions of their current and future evolution, a distinction is usually made between (i) the ongoing response to past climate changes on time scales as far back as the last glacial period, (ii) the direct effect of contemporary surface mass balance changes, and (iii) the ice-dynamic response to such mass-balance forcing and to basal melting below ice shelves. In this work, surface mass balance changes are found to be the dominant forcing for the Greenland ice sheet, whereas substantial sub ice shelf melting becomes important for Antarctic grounding-line migration on a multi-centennial time scale. The original models, based on the shallow ice approximation for grounded ice and the shallow shelf approximation for Antarctic ice shelves, are currently being extended within the ice2sea project to include higher-order representations of the force balance. This allows to include the effects of longitudinal stress gradients in the transmission of marginal perturbations on the inland flow. A novel finite-difference implementation of an incomplete second-order stress approximation ('LMLa') has been implemented on a staggered grid, having much improved stability and convergence properties compared to earlier schemes. For Antarctica, we have implemented the Schoof boundary condition to satisfy an additional physical constraint for a moving grounding line. New approaches have been tested to initialize the models for present-day conditions. Furthermore, horizontal model resolution has been increased to run model versions on 10 km and 5 km grids employing upgraded geometric datasets. The presentation will highlight current progress on our new generation of whole ice-sheet models. Our main time scale of interest is the next few centuries, but longer simulations, in part from coupled ice sheet/ ocean/ atmosphere models have also been performed.

Assimilated and Predicted Thermosteric Sea Level Changes in Near-Term Global Warming Prediction Experiments

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Initializing a coupled atmosphere and ocean model with historical oceanographic observations, near-term global warming prediction experiments have been conducted after the CMIP5 guideline. This is a challenging theme in the next IPCC assessment report. In the experiments, we are aiming at less uncertain climate predictions on a decadal time scale in specific regions. Ocean thermal conditions are also expected to be predicted through this approach. Early studies show potential predictability of decadal predictions of surface temperatures. Moreover, pacific decadal oscillations occurring in the past seem to be predictable according to our model study (Mochizuki et al., 2010), in which the model is initialized by data assimilation of oceanographic temperature and salinity observations from 1945 to the present.

Temperature biases reside in the historical expendable bathythermograph (XBT) observations. By removing depth biases which cause the temperature biases, dramatic changes appear in global mean thermosteric sea level (Ishii and Kimoto 2009). In addition, this correction leads a better prediction skill of the Mochizuki et al.'s model, in comparison with the case without the depth bias correction (Yasunaka et al., 2010).

By these research activities and related studies as well, past and future thermosteric sea level changes should be evaluated with accuracy locally on the decadal time scale.

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Projections of Relative Sea-level Change in the Canadian North

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We present projections of relative sea-level rise in the 21st century for communities in the Canadian Arctic. First, for selected communities, we determine the sea-level fingerprinting response from Antarctica, Greenland, and mountain glaciers and ice caps. Then, for various published projections of global sea-level change in the 21st century, we determine the local amount of "absolute" sea-level change. We next determine the vertical land motion arising from glacial isostatic adjustment (GIA) and incorporate this into the estimates of absolute sea-level change to obtain projections of relative sea-level change. The sea-level fingerprinting effect is especially important in the Canadian Arctic owing to proximity to Arctic ice caps and especially to the Greenland ice sheet. Its effect is to reduce the range of projected relative sea-level change compared to the range of global sea-level projections. Vertical crustal motion is assessed through empirically derived regional isobases and the Earth's predicted response to ice-sheet loading and unloading by the ICE-5G ice sheet reconstruction. Owing to the large rates of crustal uplift from glacial isostatic adjustment across a large region of central Arctic Canada, many communities are projected to experience relative sea-level fall despite projections of global sea-level rise. Where uplift rates are smaller, such as eastern Baffin Island and the western Canadian Arctic, sea-level is projected to rise.

Climate of Antarctica and South America (CASA) Project: Present State and Preliminary Results

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Since the beginning of the 20th century, the global mean surface temperature has risen approx. 0.74°C (IPCC, 2007). In the Antarctic Peninsula area, a dramatic rise of the superficial temperatures of ca. 3 degrees has been reported for the last 50 years. This main driving force working together with other processes has resulted in the collapse of several ice shelves in the region and is linked to nearby ocean warming and intensification of the circumpolar westerlies. Glaciers are retreating on the Peninsula, in Patagonia, on the sub-Antarctic islands, and in West Antarctica adjacent to the Peninsula (Mayewski and others, 2009). Although the scientific evidence for global warming is meanwhile overwhelming, the prediction of regional impacts proves to be much more problematic. Considering the lack of a longer climatic data record it is desirable to extend this information in order to understand the contribution of several other factors that feedback the mechanisms.

During the last two years, a joint international effort undertaken by Brazil, Chile and the USA focused on the recovery of an ice core at Detroit Plateau (northern Antarctic Peninsula, 64°05'S / 59°40'W). Besides being located in an area so far not covered by Antarctic ice coring, this site is situated below the -10°C isotherm, avoiding the problem of water inclusions that contam-

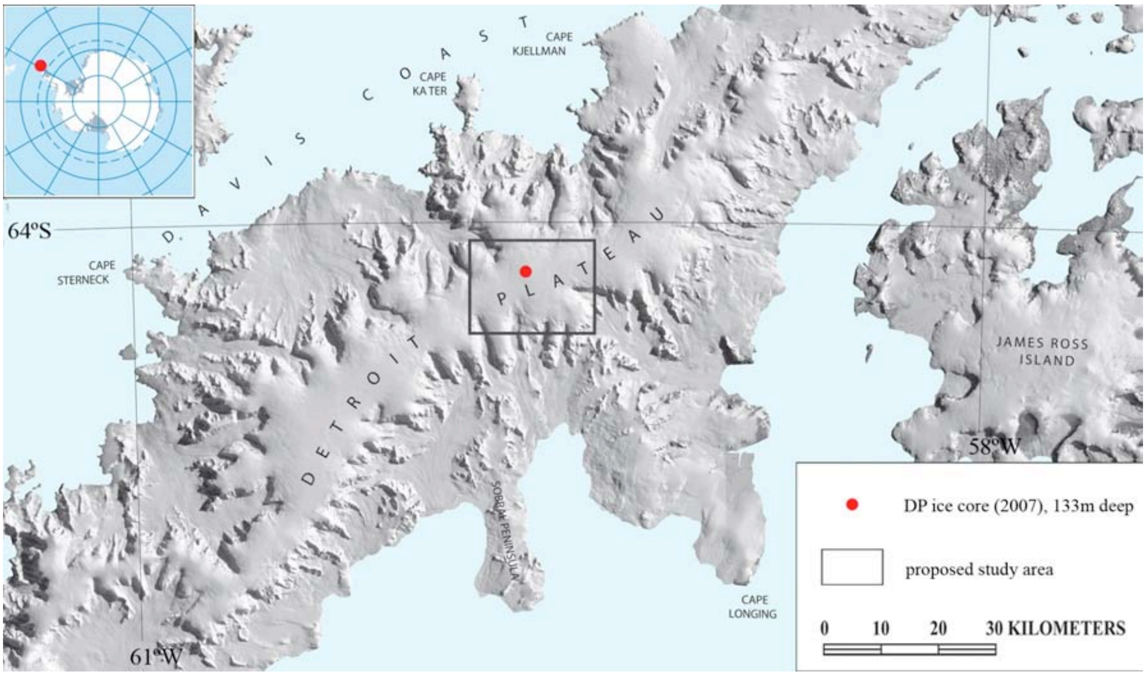

Figure 1. Detroit Plateau, Antarctic Peninsula Site. A SCAR CASA (Climate of Antarctica and South America) Project - Brazil, Chile, US, New Zealand.

inates the isotopic signal of ice beneath. Moreover, airborne radar measurements showed that the bedrock forms a basin with a maximum depth of 560 m, giving the possibility that comparatively old ice could have been trapped at this location.

Following a brief and promising pre-scouting landing in February 2007 the first field campaign at Detroit Plateau was carried out in November 2007. As a main result a medium-deep ice core (133 m) was drilled in a site located at 1,940 m a.s.l.. Additionally, numerous other measurements were compiled. This work included snow sampling for isotopic analysis, radio eco-sounding, investigations on ice dynamics and snow accumulation, DGPS measurements using Leica SR9500 equipment, installation of AWSs', meteorological observations and atmospheric aerosol measurements. The 133 m ice core is still being processed, including analyses of about 50 trace elements at ppm and ppb and ppq resolutions, moreover stable isotopes. The November 2008 field campaign stated extraordinary high snow accumulation rates (about 4 m) for the preceding winter.

An important step in reconstructing the time frame for paleoclimatic events is to calibrate climate archives like ice or sediment cores. One option is to establish time markers that allow comparison of climate signals from different regions based on relative stratigraphy. Volcanic ash layers are among those proven time markers but a crucial pre-requisite for their use as a calibration tool is the existence of data on possible source volcanoes in order to identify their origin. This data is largely missing in the Antarctic Peninsula area. The final drilling to get the long ice core it is planned for 2012.

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Sea-Level Rise Projections from Semi-Empirical Models

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The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) suggested 18–59 cm sea level rise by 2100 with an additional 10–20 cm on the upper limit associated with rapid dynamical changes in ice flow of the ice sheets (Meehl et al., 2007). Lately these IPCC numbers have been challenged with new estimates of 0.5–1.4m (Rahmstorf, 2007), 0.75–1.90 m (Vermeer and Rahmstorf, 2010), 0.8–2.0 m (Pfeffer et al., 2008), 0.8–1.3 m (Grinsted et al., 2010) and 0.6–1.6 m (Jevrejeva et al., 2010) sea level rise by 2100.

The approach used by IPCC to estimate future sea level rise has been to model the major components of sea level budget: ocean thermal expansion and ice melting. However, the observational sea level budget is not yet closed; in addition, there is some controversy about the relative importance of individual contribution from the ice sheets and glaciers melting and changes in ocean heat content and uncertainties associated with ice sheet mass balance. An alternative approach to climate model simulations for assessing sea level rise and forecasting future changes are statistical models, which are based on physically plausible semi-empirical relationships between past or predicted future global temperature changes and sea level rise (Rafmstorf, 2007; Grinsted et al., 2010, Vermeer and Rafmstorf, 2010). In latest studies (Jevrejeva et al., 2009, 2010) an inverse statistical model driven by radiative climate forcing has been used to examine potential response in sea level to the changes in natural and anthropogenic forcings by 2100. Thus mean global sea level is an independent measurement of global response than mean global temperature which has been typically the target series of both attribution studies and future modeling scenarios.

The observationally tuned statistical methods give significantly higher estimates of sea level rise those used in previous IPCC reports.

Unexplained Sea Level Rise Component (1850-2002)

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We examine the relationship between 150 year long records of global sea level (GSL) calculated from tide gauge stations and global ocean heat content (GOHC), glacier and ice sheet melting. Observations from tide gauges suggest global sea level rise of 28 cm since 1850. Contribution from thermal expansion of the ocean is only 5 cm (20%). The sea level contribution calculated from continental glacier volume changes accounts for 7 cm (25%).

We find a large unexplained sea level rise (about 1/2 of GSL) with substantial variability that is likely caused by combination of underestimating the contribution from melting ice masses, thermal expansion of the ocean as the linear trend component of about 0.9 mm/yr, and decadal variability associated with the hydrological cycle and climate–driven changes in continental water storage contribution.

Causes of Recent Sea Level Rise in the East/Japan Sea from Satellite Altimetry and In Situ Data

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The east/Japan Sea (EJS) is called as a miniature ocean, since several ocean processes such as water formation and western boundary current take place, and we have a particular interest in the oceanic processes such as sea level rise, in relation to climate change. Kang et al. (2005) examined recent sea level rise in the East/Japan Sea (EJS) through the analyses of TOPEX/Poseidon (T/P) sea level anomalies, thermosteric sea level (TSL) and long-term tide gauge data. The 9-year long T/P analyses reveal average trends of 5.4 ± 0.3 mm yr^{-1} for all of EJS and 6.6 ± 0.4 mm yr^{-1} for the southern EJS. These are much larger than the global rates of 3.1 ± 0.4 mm yr^{-1} reported by Cabanes et al. (2001) and 2.8 ± 0.4 mm yr^{-1} by Cazenave and Nerem (2004). This T/P rate compares relatively well with those from TSL data and tidal sea level gauges, indicating that sea level rise in the EJS is mainly due to thermal expansion. The southern EJS shows a non-uniform sea level trend pattern, with the western part of the Ulleung and Yamato basins having values of 10 mm yr^{-1} and larger. This non-uniform pattern is discussed in terms of variable thermal expansions arising from a recent decadal trend in the temperature anomaly in the upper layer of the two basins.

In addition to this study the possible contribution by halosteric sea level effect is investigated and the limitation is discussed under present environment. Relatively high sea level rising rate is seen to exist since previous estimation (Kang et al., 2005). The progress is reported in the poster.

Glacier Contributions to Sea Level Rise: Past, Present and Future

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Glaciers and Ice Caps (GIC) are losing mass and are among the most significant reasons for mean global sea level rise.

- How much water is stored in GIC?
- How much water is presently released from GIC?
- How much is due to calving into the Ocean?
- Can the dynamics of marine based GIC change?
- How certain are we about all this?

The perspective is on measurements and observations.

Since AR4, estimates of the total amount of water stored in GIC have been confirmed to be slightly more than 0.5 m SLE and uncertainties have been narrowed. Estimates of the rates of mass loss and respective sea level rise have been improved by the assimilation of additional data and have been updated. During the first pentad of the 21st Century about 1.2 mm SLE/yr came from GIC, the present (as yet incomplete) pentad delivers slightly less (about 1 mm SLE/yr).

Uncertainties for total mass estimates and changes are mainly due to incomplete area inventories of GIC, the very small although increasing number of glacier volume measurements, and uncertainties in the widely applied area-volume scaling techniques. Mass change rates suffer from undelivered primary point measurements and from heterogeneous measurement and analysis techniques. In addition, the geographical and size distribution of monitored glaciers is uneven and measurements are insufficient or even totally missing in some parts of the world. Particularly in high mountain ranges measurements are usually limited to very small glaciers for logistic reasons and because they are often carried out for reasons other than climate studies. There is only a vague idea about the total amount of mass loss due to calving from tidewater glaciers (those that reach sea level). Potential dynamic instabilities of mostly large tidewater glaciers in high latitudes are practically unknown but, even if for short terms only, of potentially significant impact on sea level rise. Respective research activities and funding are unsatisfactory. There is little knowledge about both the extent and the change rates of GIC surrounding the ice sheets in Greenland and Antarctica.

It is concluded that understanding of GIC is considerably better than that of other SLR components. They are presently contributing around 1 mm SLE/yr, and they will most probably remain major contributors to SLR throughout and beyond the 21st Century. Despite the relatively small uncertainty, there is large potential and also need for improvement.

Sea Level Contribution from Mountain Glaciers and Ice Caps

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We will present an assessment of the presently available knowledge and information about glaciers from different mountain regions and from the ice caps as reconstructed from the past, as extrapolated from recent measurements, as estimated for the near future, and as simulated from modelling. Differences to previous estimates and uncertainties will be addressed.

Exploring High-End Scenarios for Local Sea Level Rise to Develop Flood Protection Strategies for a Low-Lying Delta

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Sea level rise, especially combined with possible changes in storm surges and increased river discharge resulting from climate change, poses a major threat in low-lying river deltas. In this study we focus on a specific example of such a delta: the Netherlands. We develop a plausible high-end scenario of 0.55 to 1.10 meters global mean sea level rise, and 0.40 to 1.05 meters rise on the coast of the Netherlands by 2100 (excluding land subsidence), and more than three times these values by 2200. Together with projected changes in storm surge height and peak river discharge, these scenarios depict a complex, enhanced flood risk for the Dutch delta.

Pakistan's Coastal Zone – In a Climate Change Scenario

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Pakistan has over 30% of its population living in the vicinity of the coastal zone, over 20% of coastal area of Pakistan is relatively developed, 40% of industry is situated on or near the coast. Protecting these human assets will be costly, particularly if the effects of climate change are sudden rather than gradual. A rise sea level of a few mm per year, although not threatening but direct and indirect impact of this rise would have a profound impact on the coastal resources for sustainable coastal zone management. Direct land loss of low-lying areas can rapidly damage or destroy coastal ecosystems. In addition to sea level change a rise in global warming will also increase the frequency of tropical cyclones and will further add to the miseries of the coastal states. Pakistan's coastline with the Arabian Sea stretches to over 990 km. It comprises two distinct units in physiographic outline and geological characteristics. The coastal and offshore geology of Pakistan tectonically exhibits both active and passive margin features.

The impacts of the hazards resulting from progressive climate change are apparent all along the coast. The adverse effect of sea level rise on the Pakistan coast is expected to be pronounced in the Indus Delta. Topographically it is a tidal flat zone. A sea level rise of about 2 metres is expected to submerge or sea encroach an area of about 7,500 sq km in the Indus Delta. The low-lying areas along the Baluchistan coast may also exert a significant effect. The mean sea level (MSL) along the coast at Pasni is about 1.4 m from the chart datum. The MSL is slowly but gradually rising at a rate of about 1.1 mm/year. Although a small sea level rise may be compensated by tectonic uplift rate of the Makran coastline estimated at 1-2 mm/year at Ormara.

The existing information and data on SLR in the archives of the National Institute of Oceanography, Karachi, concurs with the world average rate of increase in sea level. The rate of sea level rise in Pakistan coastal region has been tabulated to approximate 1.1 mm per year. The effects of changes in regional climate have been seriously felt since the past two decades.

Currently scientific sea level information and data in Pakistan is insufficient to reconstruct any quantitative change. It would be pertinent to use eustatic sea level increase of 2 mm/year and 6 mm/year in order to predict possible scenarios for the Pakistan coast for the next 50 and 100 years. These are used as best estimates for sea level rise assuming "business as usual" worldwide emissions. The available Sea level data recorded in Karachi for the past 100 years has been tabulated. The correspondence in their increasing trends, may appear trivial but it clearly suggest, that global warming has had a significant effects on the sea level rise since the 1900. Three scenarios - including the existing rate of 1.1 mm/year are shown in Table 1. More important than the actual rise in sea level is the possible increase in the frequency and severity of storm surges, which combined with sea level rise, could result in devastating floods in the region. This sea level increase will cause stronger wave action, higher tidal amplitude and greater possibility of surge occurrence that will have significant socio-economic effects on the coastal regions. The combined consequential effects of these coastal processes have been observed in many parts of the Balochistan and Sindh coast. The coastal lowlands around the coastal areas are particularly vulnerable to further change in sea level rise and related coastal processes.

Prior to assessing the impacts of projected rise in sea level and the associated climate change, it is essential to understand the general characteristics of Pakistan's marine and coastal areas and the active dynamical physical processes.

Table 1. Sea Level Scenarios

Rate of rise	After 50 years	After 100 years
1.1 mm/year	5.5 cm	11 cm
2.0 mm/year	10 cm	20 cm
6.0 mm/year	30 cm	60 cm

The observations and available data of dynamic coastal processes along Pakistan coast clearly indicate that the sea level is rising quite rapidly. This will lead to high investment costs in protective measures. Low-lying deltaic coast of Indus is especially vulnerable to a rising sea level, and to other events such as increased in frequency and intensity of storms, increase in precipitation followed by long spells of drought. Inundation, flooding, erosion and intrusion of seawater are among the likely impacts. Such impacts would affect productivity and seriously compromise economic well being.

Combined Use of a Variable Resolution GCM and Physical Downscaling Methods for Studies of the Antarctic Surface Mass Balance

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Coupled model climate projections indicate increasingly positive surface mass balance (SMB) for the Antarctic Ice Sheet as a whole because the projected accumulation increase, induced by a higher moisture holding capacity of the atmosphere directly linked to warmer air temperatures, is thought to overcompensate for increased surface melt rates at the ice sheet margins (e.g., Gregory and Huybrechts, 2006; Krinner et al., 2007). Consequently, the Intergovernmental Panel on Climate Change (IPCC, 2007) reports that for stabilisation in 2100 with SRES A1B atmospheric composition, Antarctic SMB would contribute 0.4 to 2.0 mm yr–1 of sea level fall. This means that although the sign of the contribution of the Antarctic SMB to future sea-level changes appears fairly certain, its amplitude is poorly constrained and thus constitutes a large source of uncertainty in sea-level change projections. Krinner et al. (2008) and Genthon et al. (2009) report that climate models with finer horizontal resolution tend to predict a larger precipitation increase. This is linked to the fact that about three-quarters of the continental-average precipitation rise originates from the marginal regions of the Antarctic ice sheet with surface elevation below 2250 m (Genthon et al., 2009). Moreover, actual and potential future ablation areas are also confined to the ice sheet marginal areas. Therefore, high-resolution climate model simulations or downscaling techniques are required to reduce uncertainties of projection of future Antarctic SMB changes. Here, we use an atmosphere-only general circulation model (GCM) with regional high resolution (60 km) to produce a set of simulations of the Antarctic climate and SMB during selected periods of the 21st century. We prescribe anthropogenic forcing following the SRES-A1B scenario and sea-surface conditions (SSC: sea-surface temperature and sea-ice fraction) using the oceanic output of coupled ocean-atmosphere CMIP3 climate projection runs. The need to choose sea-surface conditions from coupled climate model output immediately gives rise to some questions. First, should SSC be directly taken from a coupled model (both for the control simulation and the climate projection) or, alternatively, should one use an anomaly method in which the present-day observed SSC are used for the present-day control simulation and the climate change signal (i.e. ocean surface temperature and sea-ice fraction changes) from a coupled model climate change experiment is added to the observed present SSC to obtain boundary conditions for the atmosphere-only climate change experiment? Krinner et al. (2008) showed that the use of an anomaly method clearly improves the representation of the present climate in the atmosphere-only control simulation for the obvious reason that in this case, the inevitable systematic biases of oceanic boundary conditions from a coupled model are not imported into the atmosphere-only climate change projection. Krinner et al. (2008) argue that this should also increase the confidence in the simulation of the future climate. In this respect, it is noteworthy that anomaly methods will be used in CMIP5 atmosphere-only experiments (Taylor et al., 2009). Another advantage of the use of anomaly methods in prescribing oceanic boundary conditions for atmosphere-only climate projections is that only one present-day atmosphere-only control experiment has to be carried out, because this experiment is carried out with prescribed observed sea-surface conditions.

A second question that arises when designing an atmosphere-only climate change experiment is: How sensitive will the projected climate be to the choice of the oceanic boundary conditions? In particular, given that CMIP3 climate change experiments were carried out with about 20 different climate models, how important is the choice of the coupled model from which the sea-surface condition change signal is taken? This latter question clearly warrants assessment although the anomaly method certainly reduces the impact of the choice of the coupled model for the oceanic boundary conditions for the atmosphere-only simulations because one does not use the coupled model's absolute output, but only the climate change signal which, it is generally hoped, is less model-dependent. In the particular case of Antarctica, it was shown that the climate variability of this region is rather decoupled from oceanic forcing (Connolley, 1997, Krinner et al., 2008). However, the average ocean forcing is clearly of importance for the Antarctic climate, most notably in the coastal regions (Krinner et al., 2008). This is less the case in the plateau regions because the inversion, particularly in winter today, tends to confine the effect of oceanic changes to the lower atmosphere around the Antarctic coast. But because the coastal regions are critical for future continental SMB changes, prescribed SST are certainly critical boundary conditions (BC) for atmosphere-only climate projections.

In recent work, we used SSC anomalies from 5 coupled models to evaluate in detail the role of imposed SSC anomalies taken from different coupled model simulations in projections of 21st century Antarctic climate change with one atmosphere-only GCM. The SSC anomalies are taken from CMIP4 coupled model SRES-A1B scenario climate change experiments available from the IPCC data distribution centre. We use the SSC anomalies from the first ensemble runs of the CNRM-CM3, MPI-ECHAM5, IPSL-CM4, HADCM3 and MIROC3.2 hires models. We thus have five simulations, differing by the imposed SSC anomalies, for each of the two future periods (2030-2050 and 2070-2099). We focused in particular on the relative impact of the choice of oceanic BC in the ice sheet's marginal and central regions, and on the influence of these BC on simulated near-surface climate (more specifically on surface air temperature, precipitation, and melt rates). Our results show that this influence is very strong in the ice sheet marginal areas, stronger than one might expect given that only ocean surface anomalies were used from coupled models, not the coupled models' absolute ocean surface output. As shown in previous work, it appears that continental-scale relationships between temperature and precipitation changes are robust and fairly invariant. However, on sub-continental scales, the imprint of the variable oceanic forcing on circulation anomalies is large and thus determines to a large degree the regional-scale patterns of temperature and precipitation changes.

Future work will consist of using a physical precipitation disaggregation scheme (Gential, 2007; Gallée et al., in prep.) to downscale the simulations results obtained with the high-resolution atmospheric general circulation model. This will produce higher-resolution precipitation change projections needed for a better assessment of the effects of Antarctic SMB changes on future sea level.

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Estimation of Past Sea Level Rise and Its Causes

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The evolution of global sea level rise since 1900 is estimated from time series of coastal tide gauges. The technique applied uses neural networks which can account for relative land rise/fall without prescribing a specific GIA model. Results show an almost linear rise plus interannual variability and can be used to calculate confidence intervals.

In a separate study sea level rise as observed from satellite altimetry is assimilated in a global ocean general circulation model to separate and quantify different contributions:

- steric expansion in a warming ocean,
- redistribution without a change in the global mean and
- anomalous inflow of fresh water from land and melting grounded ice.

Our analysis shows a large contribution by deep ocean warming both between a depth of 700m and 2000m as well as in deeper layers.

Wind and Snow Related Uncertainties in Antarctic Mass Balance

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Approximately 2000 gigatons of snow accumulates on the Antarctic ice sheet each year, and roughly the same mass of ice is lost through iceberg calving and basal melting of floating ice shelves. The pathways along which this mass balance is achieved include many sources of uncertainty due to snow processes on the surface of the ice sheet and in the atmospheric boundary layer (Figure 1). Sublimation of snow resting on the ice sheet surface, blowing snow sublimation, and the scavenging of blowing snow particles as nucleation surfaces for new precipitation lead to high rates of moisture recycling in the continental interior. Snow blown from the ice sheet into the ocean is difficult to deconvolve from near-coastal ocean surface meltwater signals, and snow forms the major constituent of mélange in iceberg calving rifts.

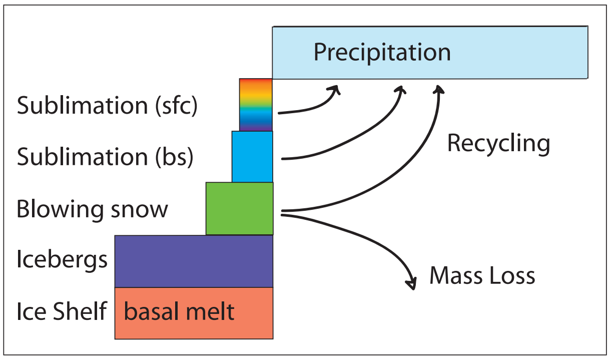

Figure 1. Relative magnitudes of Antarctic mass balance components, and pathways along which snow can impact our understanding of these processes.

Determining precipitation amounts from the accumulation of snow on the Antarctic ice sheet is complicated not only by moisture recycling between surface and atmosphere, but also by more direct wind-related processes. Antarctic precipitation is particularly difficult to measure due to its fine particle sized snow that is easily transported over great distances even at very low wind speeds. When snowfall was directly measured at Dome C, its timing appeared to have little or no relationship with the timing at which that new snow stuck to the surface: accumulation only happened in association with strong wind events (Groot Zwaaftink et al., 2010). Over sea ice near West Antarcica, the ratio of precipitated to accumulated water mass was 3:1 due to significant wind erosion of snow (Leonard and Maksym, 2010). New snow can also accumulate temporarily in the form of dunes, portions of which become sastrugi that can remain in place for months to years before either sublimating or being redistributed across the ice sheet by the wind (Leonard, 2010).

If precipitation over Antarctica has increased in recent decades as anticipated in many global warming scenarios (Huybrechts et al., 2004), it has not produced a statistically significant change in continent-wide accumulation (Monaghan et al., 2006). This may be due to a multi-decadal increase in wind speeds observed at coastal stations over the late 20th century, reported by Turner et al. (2005). Higher winds would increase the rates and magnitudes of Antarctic precipitation recycling and the mass of blowing snow lost to the ocean. This means there could have been an increase in Antarctic precipitation without a corresponding sink for that water mass on the continent. Stronger wind speeds may also explain why satellite altimetry-based studies have indicated recent increases in accumulation (Davis et al., 2005), since higher winds could increase the prevalence and magnitude of sastrugi on the ice surface. Maksym and Markus (2008) compared ERA-40 accumulation with that of Arthern et al. (2006) and found that the atmospheric reanalysis showed lower accumulation in the continental interior and higher accumulation near the coasts compared with the microwave emissivity based map. These patterns coincide with the regions where sastrugi would be most likely to lead to overestimates of accumulation in remote sensing studies and wind erosion of snow from the ice sheet to the ocean would lead to less accumulation than predicted by atmospheric models.

The increase in Southern Ocean storminess responsible for the rise in wind speeds appears to result from intensification of the Southern Annular Mode over recent decades (Marshall et al., 2004). If this recent trend in the SAM does not continue, and net precipitation is rising, the Antarctic will begin to accumulate more snow. Even a small decline in wind speed may lead to significant decreases in wind transport of snow, in sublimation rates, and in the recycling of that moisture along coastward trajectories. Field-based quantification of the current magnitudes of wind transport of snow and of moisture recycling in the Antarctic atmospheric boundary layer are critical to evaluating the hypothesis presented here, that wind transport of snow may be capable of masking significant trends in precipitation.

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Sea Level Contribution From Ocean Warming and the Great Ice Sheets - RCP-Scenarios for the 21st Century and the Longer-Term Perspective

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We present projections of global mean sea level rise for the 21st century based on the new Representative Concentration Pathways RCP which are designed to span the entire range of possible future evolution of atmospheric greenhouse gas concentrations. For these scenarios we provide sea level contributions from (1) oceanic thermal expansion using an oceanic general circulation model embedded in a coupled climate model of intermediate complexity, (2) Greenland ice loss using SICOPOLIS in combination with the surface mass balance model REMBO with parameters constrained by paleodata of the last interglacial and (3) ice discharge from Antarctica through surface warming and basal melting using the Potsdam Parallel Ice Sheet Model, PISM-PIK, which incorporates a new representation of fast ice streams and freely evolving grounding line and calving front.

Using the same models we present a long-term perspective of the respective contributions ranging from several centuries up to 10000 years under different global warming stabilization scenarios.

Projections of Sea-Level Rise: From Global to Regional Scales

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Policy makers and planners use projections of future sea-level rise for a range of planning purposes. Sea-level rise is an important consideration for mitigation policy. This is because of potential irreversibilities or triggers for accelerated sea level change, which form a key part of our understanding of "dangerous climate change", and because of the long timescales relative to surface temperature over which sea level approaches a new equilibrium. There is thus a growing need to understand the benefits of emission reduction in terms of a wider range of environmental variables, such as sea-level rise, and move beyond the current focus on temperature. Adaptation planners need projections as one of the tools to optimise the type and timing of adaptation measures. Increasingly both policy makers and planners are asking for the most likely future changes, and the upper limit of changes.

Here we consider the current state-of-the-art for projecting sea level rise for the 21st century. Beginning with global sea level, we highlight that there are now a number of ways of providing information on future changes. Taking the global 21st century sea-level rise estimates from recent studies gives a range of around 20cm to 2m, when both emissions and science uncertainties are considered. A key aspect of the next IPCC assessment could be to discuss whether the different approaches taken to give the various ranges of projected sea-level rise are all valid, and then attempt to narrow this range.

Sea level is not expected to rise by the same amount everywhere, due to changes in ocean circulation and density distribution (Figure 1). Within individual models there is a growing understanding of the mechanisms that lead to regional changes, but the spread across models is still large. A priority research question is whether the range of modelled regional changes can be narrowed by combining the projections with observation-al constraints. For scenarios with large contributions from ice melt it is also necessary to include the spatial patterns associated with glacial isostatic adjustment.

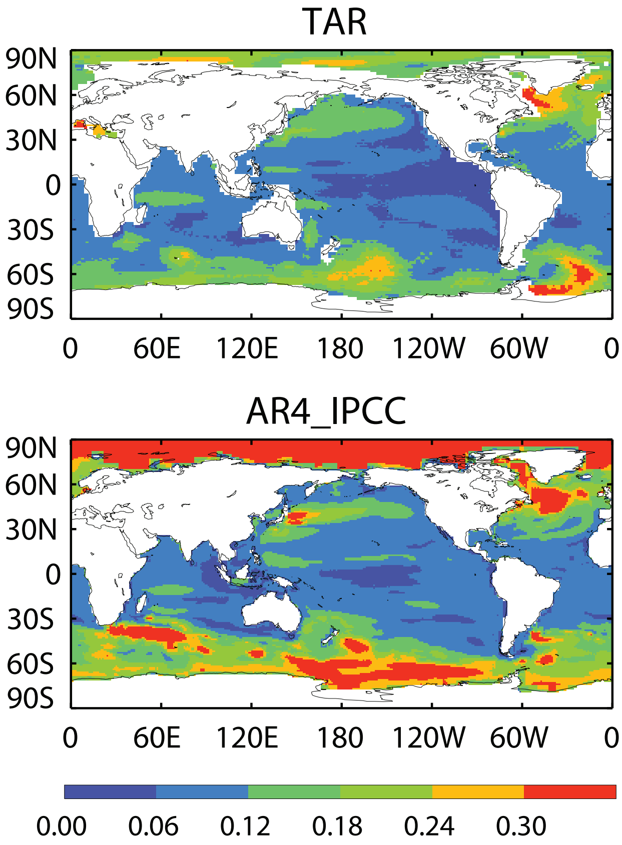

Figure 1. Projected spread of regional change relative to the global mean over the 21st century using results from both the third and fourth assessment report. The scale shows 2x the standard deviation (m) across the models.

For impacts studies even more localised sea-level rise projections are required, to account for changes in storm surges. By their very nature this type of study typically requires high resolution atmosphere and regional climate models to be used, and there is currently limited information from such studies along most of the global coastline. For the United Kingdom region, recent work on this aspect of sea-level rise has shown the importance of adequately sampling long period variability in atmospheric storminess in order to separate long-term trends from natural variability. For some locations wave simulations are also needed to give changes in extreme water level.

Mechanism and Timing of East Antarctic Ice Sheet Recession

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The recession of polar ice sheets over geological timescales is thought to be driven by changes in the oceanic environment at their margins either via rising sea level (Denton et al., 1986), increasing ocean warmth (Mercer, 1978; Alley et al., 2007), or some combination thereof (Huybrehts, 2002; Pollard and DeConto, 2009), yet empirical evidence to support or refute this theory is absent for most of the continental margin of East Antarctica. Using a combination of land (Mackintosh et al., 2007) and marine (Leventer et al., 2006) based geology and numerical ice sheet modelling (Pollard and DeConto, 2009), we present a reconstruction of East Antarctic Ice Sheet recession across the Mac.Robertson Land shelf through the last glacial termination from approximately 20,000 years ago to the present. We associate empirical and ice sheet modelling evidence of ungrounding of the ice sheet, and its subsequent thinning and retreat, with empirical proxy records of rising local sea level (Fleming et al., 1998; Peltier, 2004) and warming of the Southern Ocean (Barrows et al., 2007; Anderson et al., 2009). Recession of the ice margin was delayed compared to that of Northern Hemisphere ice sheets (Clark et al., 2009), beginning ~14,000 years ago. Most of the ice retreat occurred after 12,000 years ago, and the ice margin stabilised ~7,000 years ago. Initial ungrounding is associated with sea level rise and later retreat with oceanic warming. Secondary control exerted by local variability in shelf bathymetry led to regional differences within a general pattern of deglaciation. Retreat more-or-less ceased once sea levels and ocean temperatures had stabilised. We propose that these data constitute a first empirical validation from the East Antarctic margin of previously untested theories concerning ice sheet–ocean linkages.

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The Effect of Meteorology on Sea Level Variations at the Island of Zanzibar

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Meteorological and tide gauge data were used to analyze the monthly variations of sea level in Zanzibar over the period 1985-2004 through spectral and multiple regression analyses. Results indicate that the monthly sea level variations are predominantly composed of semi-annual, annual and 4-year oscillations. These variations are represented by steric effect proxies of rainfall and air temperature (45%), southeast and northeast monsoon winds (41%), and air pressure (5%). There is also a declining trend of sea level (9%), which is mainly influenced by northeast winds. The semi-annual cycle of sea level (28%) is largely dominated by southeast winds (15%), with the remaining 13% of the variance being equally represented by rainfall, northeast winds and air pressure. The annual sea level component (36%) is represented by rainfall (11%), air temperature (10%), southeast winds (8%) and northeast winds (7%). The 4-year oscillations, which account for about 27% of the variance fitted on sea level, are mainly represented by air temperature (12%), rainfall (8%) and southeast winds (6%). During the 20-year study period, air pressure and rainfall have remained relatively constant, but there are trends of sea level, northeast winds, southeast winds and air temperature.

Contributions From MAGICC to AR5: Quantifying Uncertainties in Global and Regional Sea Level Rise (SLR) Projections

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The propagation of uncertainties along the chain of effects from emissions to global and regional sea level rise projections is challenging. The task is to combine uncertainties in the carbon cycle, other gas cycles, radiative forcings, global-mean temperature response and regional climate effects with the induced contributions to sea level rise and its regional pattern over time. One option is to represent the combined effect of the uncertainties by parameterising and emulating the range of responses of high-complexity models along each step of the cause-effect chain, and combining these uncertainties probabilistically. This method of combining uncertainties has previously been accomplished with the low-complexity model MAGICC (Wigley and Raper, 2001; Meinshausen et al., 2008) with global-mean temperatures being the end of this probabilistic analysis chain (Wigley and Raper, 2001; Meinshausen et al., 2009). It is possible to expand this type of probabilistic assessment to cover changes in sea level, although the complexity of the analysis is increased considerably by the incorporation of uncertainties in sea level rise components (e.g., WAIS, Greenland, small glaciers (Raper and Braithwaite, 2006; Raper and Braithwaite, 2009) and regional effects.

As an example of an individual contribution to sea level rise uncertainty we consider a simple parameterisation for the contribution from Greenland. We present a method that combines probabilistic global-mean temperature projections based on IPCC AR4 science, with regional climate uncertainty distributions based on 22 CMIP3 AOGCMs (Frieler et al., in preparation), and uncertainties in the determinants of the potential contribution from Greenland. This approach allows one to derive exceedance probabilities for Greenland's contribution to sea level rise (Gregory and Huybrechts, 2006) – depending on cumulative carbon emissions from 2000 to 2100.

A more comprehensive study, drawing on state-of-the-art knowledge of individual contributors to SLR, could produce probabilistic global and regional sea level rise projections under different scenarios or different emission budgets.

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Mountain Glaciers Instability in Central Asia During Last Decades and its Impact to the Runoff

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Mountain glaciers being unique long term resource of fresh potable water still attract specific attention to their evolution both in the past, present and in the future time in Central Asia. Five countries of Central Asia (Kazakhstan, Kyrgizstan, Tajikistan, Turkmenistan and Uzbekistan) are situated in the basins of two main rivers Amudarya and Syrdarya that are originated in the mountain runoff forming zones with significant area of glaciation. These countries are faced to the problems that are characteristics for all transboundary ones (Separated in terms of driven interests of available water resources use and jointed in terms of necessity to provide the rational water management for all involved trans-boundary bodies and countries). The control, reliable evaluation and adequate management of water resources available and limited under climate change upcoming and emerging stresses related to conflict of interests, discrepancy in water demands and available water supplies etc. are to be addressed.

It is noteworthy that reliable evaluation of the evolution the glaciation is not trivial task owing to the fact that factors affected to glaciation are extremely heterogeneous in both spatially and time. The glaciation is characterized by great extension in latitude and in longitude, wide glaciers variation by their types and sizes, their quite different aspects to the prevailing air mass bringing precipitations and to the shielding mountain ranges that could explain the different responses of glaciers to the climate change.

It is obviously that the glaciation retreat has been going on for last decades with background of continuous positive trend of air temperature. Rates of glaciation retreat are varied from region to region and by morphological glaciers data.

It is remarkable that first large scaled endeavor to get evaluation the area of glaciation being representative by both spatially and in time was succeeded by 1957. The results are the first reference points for further evaluations had been completed. More reliable and comprehensive glaciers inventories were completed for Pamir-Alay, Interior Tien Shan, North Tien-Shan , Western Tien Shan and Djungar Alatoo in Central Asia.

For example the rate of glaciers degradation on the Pamir Alay made up 11.7% of area by 1957 for the period 1957-1980. For North Tien Shan it made up 16.6% for the time period 1955-1979 and 23.9% for 1979-1990. Glaciers inventory of Interior Tien Shan (Akshyirak range) gave data on 3% of glacial degradation for 1943-1977 and 12% of glacial degradation for Djungar Alatoo during 1956-1972. Data of glaciers inventory in the Western Tien Shan say that rate of glacial degradation here is 9.5% for 1957-1980 and 23.7% for 1957-2001.

The evolution of glaciation is depended on climate factors such as air temperature, precipitation, solar radiation, evaporation and also on how much glaciers are responsive to the climate change.

Among the factors mentioned above the continuous global and regional air temperature growth during XX century and that the process given is ongoing for XXI century are well known.

It is important to know on the rate of differences in summer averaged air temperature over long time period. Data of meteorological station "Tien-Shan" as representative one to establish of relationship between ratio of glaciation reduction and mean summer air temperature were used.

The same data were applied to calculation of glacial retreat projections for 2000-2020.

The averaged rates of glaciation reduction were calculated on the base the earlier derived relationships between observed data on glaciers retreat and local air temperature anomalies.

Thus the keeping of recent tendency of summer air temperature growth in the Central Asia mountain and good forecast of the glacial degradation ratio in the future the prevailing glaciation area in the Amudarya and Syrdarya river basins will go down on 1107 km^2 and will make up 77% of its area in 2000.

The relative error between glaciers area by the processed satellite images (TERRA) and proposed method makes up 2-3% that proves method's good efficiency.

The automated informational system being based upon the modules of the mathematical models of transformation the runoff's components to the runoff and river runoff forming process including the rain, glaciers and snowpack contributions was used to proceed with exploring the impact of glacial degradation to the runoff. The principle design of system given allows to ingesting data input (air temperature, precipitation, glaciation and snowpack areas rate) by scenarios way.

Experts assessment of the vegetative runoff for particular rivers of Central Asia with help system above that ingested climate change scenarios and glacial retreat projections data input for 2020 had been completed. The results didn't show any significant changes in runoff for time period under consideration. But it is expected that further glacial retreat will negatively affect to runoff for long term perspective that will exaggerate the existing water stresses to economics of transboundary countries.

Global, Regional, and Local Sea Level Rise on the U.S. Atlantic Coast: Atlantic City as the New Atlantis?

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The geological record provides perspective on sea-level change, including global, regional, and local processes and rates of change. We have reconstructed global sea-level variations over the past 100 million years, showing that: 1) glacial eustasy occurred during the greenhouse world of the Cretaceous through Eocene, with typical changes of 15-25 m (i.e., up to about 1/3 of the present-day 65 m stored as ice); 2) large continental scale ice sheets appeared in Antarctica during the early Oligocene (33.8 Ma); 3) following a peak of sea level of 20 m in the early Pliocene, large northern hemisphere ice sheets caused sea-level change of 120 m; and 4) the maximum global rate of sea-level rise from 5000 ka to 1850 A.D. was 0.75 ± 0.25 mm/y. Recent studies have documented that the 20th century global sea level rise was 1.8 ± 0.3 mm/y, but has accelerated over the past 15 yr and is rising today at 3.3 ± 0.4 mm/y. Thus, we attribute <<30% of the modern global rise to natural causes. The IPCC best estimate, that global sea level will rise 40 cm by 2100, is too low: we are currently tracking a minimum global rise of 80 cm by 2100. The maximum global rise is poorly constrained but maximum rates observed during meltwater pulse 1A are ~40 mm/yr. We suggest a maximum global rise of <2 m by 2100 A.D. (best estimate 1.2 ± 0.4 m). Regional and local subsidence, ranging from 1-2 mm/yr along the U.S. east coast, exacerbates the global rise. Regional subsidence is caused by isostatic adjustments to removal of the Laurentide ice sheet and/or sediment loading; local subsidence is typically caused by groundwater withdrawal and compaction. Together, these three effects will cause a minimum of ~1 m of rise along the U.S. Atlantic seaboard resulting in loss of land (1-3%), loss of marshland, and higher beach erosion. The effect of global temperature rise on storm intensity and frequency are not clear, but sea-level rise will exacerbate flooding during storms. By 2100 much of the New Jersey barrier islands will be impacted causing flooding of bays, streets, and Newark during peak storm surges.

Observations of Recent Sea Level Change

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With the launch of TOPEX/Poseidon (T/P) in 1992 and the subsequent launch of Jason-1 (2001) and Jason-2 (2008), we now have a precise 17-year continuous record of sea level change. Global mean sea level change (Figure 1) has been going up an average of 3.4 mm/year, with substantial interannual variation due to ENSO-related processes (Nerem et al., 2010). The analysis of in situ temperature and salinity measurements shows that most of the observed spatial variation in sea level rise is due to thermosteric variations.

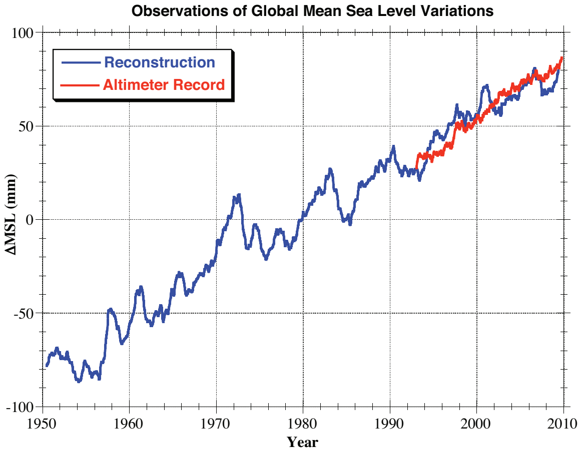

Figure 1. Variations in global mean sea level from a) the satellite altimeter record from TOPEX/Poseidon, Jason-1, and Jason-2, and b) a reconstruction from the tide gauge record and a set of EOFs computed from satellite altimetry.

Two more developments have fundamentally improved our capability to study the causes of sea level change: the launch of the GRACE satellite gravity mission and the establishment of the Argo network of profiling floats. Together, satellite altimetry, satellite gravity, and Argo measurements have provided unprecedented insight into the magnitude, spatial variability, and causes of present-day sea level change. These results will be reviewed and compared to historical measurements of sea level change from the tide gauge network. The main conclusion is that the rate of sea level rise has roughly doubled and there is evidence that this increase in the rate occurred approximately in the early 1990s (Merrifield et al., 2009). The satellite measurements also give a perspective on the spatial variability of sea level change not possible with only tide gauge measurements. We will present results showing that these three measurement systems close the sea level budget within their error bars, i.e., total sea level measured by satellite altimetry equals the ocean mass change measured by GRACE plus the thermosteric sea level change measured by the Argo network (Willis et al., 2008; Leuliette et al., 2009). These are powerful tools for studying sea level change and it is imperative that they be continued.

Satellite altimeter measurements can be combined with historical tide gauge measurements to reconstruct sea level change prior to the satellite era. A variety of different studies (e.g., Church and White, 2006) have attempted to reconstruct past sea level change using a combination of EOFs derived from satellite altimeter measurements and long time series of sea level measurements from tide gauges. These sea level reconstructions are then used to determine the relationship between surface temperature changes and sea level change, which can be used to project future sea level change given various scenarios for future warming. However, the errors in the sea level reconstructions are large, and thus can have a large impact on the future sea level projections (Rahmstorf, 2007). We have developed our own methods for performing sea level reconstructions (Hamlington et al., 2010) and have examined the sensitivity of the reconstructions to three different factors: 1) the weighting of the tide gauges used in the reconstructions, 2) the selection of the particular tide gauges used in the reconstructions, and 3) the choice of EOF method used for identifying variability modes in the satellite altimeter measurements. We will present results on the sensitivity of the reconstructions to these variables, and we will use this to establish an error budget for different methods.

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The Implications of Regional Bounds on Ice Sheet-Driven Sea Level Rise Projections

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Sea-level rise (SLR) projections are critical to climate change mitigation and adaptation efforts, but their utility is limited by the uncertain climate response of continental ice sheets. The IPCC's fourth assessment report (AR4) emphasized the thermosteric and mountain glacier contributions to near-term (pre-2100) SLR, without a detailed estimation of the ice sheet contribution (e.g., an upper bound or a probability distribution). The adequacy of this approach for policy purposes has been questioned (e.g. Oppenheimer, et al., 2007), with some critiques arguing that quantitative SLR assessments may be detrimental to policy-making if they do not encompass a more complete range of outcomes. The treatment of the long-term (beyond 2100) ice sheet contribution in AR4, based on current models and paleoclimate assessment, was quite general. A truly informative risk management approach to both the near and long term problems would be fully probabilistic, as opposed to presenting point estimates or upper bounds. Recent analyses have attempted to supplement AR4 projections using three approaches: "semi-empirical" (e.g., Vermeer and Rahmstorf, 2009) and "kinematic" constraints (e.g., Pfeffer et al., 2008) on the upper bound for the near-term ice sheet contribution, and probabilistic representation of paleoclimate analogs for the rate and magnitude of long-term SLR (Kopp et al., 2009).

Kinematic methods may limit the spatial extent of the analysis (e.g., the Amundsen Sea sector of Antarctica or fast-moving Greenland glaciers (Pfeffer et al., 2008)). Though these bounds may provide a plausible upper limit to near term SLR, this choice excludes sources of sea level rise relevant to policy decisions. Taking a Bayesian view, the elimination of certain regions from an assessment is a subjective decision that strongly limits the prior probability. Because the range of possible SLR may be more important than the current estimate of most likely outcomes, and because of deeply uncertain scientific underpinnings, any constraints imposed on the prior should be carefully examined.

Here, we address the implications of spatial bounding using a twofold strategy: reviewing historical precedents in SLR prediction and other environmental risk assessments, and conducting a simple analysis to assess the impact of SLR originating from outside the "region of interest". In aggregate, these efforts suggest that the choice to completely ignore regions of ice sheets should be approached with caution. Because science may be steered by the assessment process, further reinforcement may be derived from focusing of scientific resources on ice sheets/regions currently of interest. Regardless of their quantitative limitations, more robust approaches may offer complementary insight for decision support.

As the next generation of numerical models are integrated into SLR assessment, it is likely that computational and observational constraints will exert additional pressure to bound "regions of interest". The approach employed in this paper may serve as a framework to track the learning process, allowing revisitation of the sources of uncertainty as more is learned about both ice sheets and future climate forcing.

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Is Bidecadal Sea-Level Oscillation Amplifying in a Part of the Mediterranean Sea?

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As shown by Unal and Ghil (1995), long-term variability of the Mediterranean sea level is dominated by decadal signal in the west and extreme east parts of the basin and by bidecadal signal in the Adriatic Sea located in between. Adriatic bidecadal oscillation was detected already by Polli (1947) in the Trieste and Venice tide-gauge data, and was more recently observed in time series collected at four Croatian stations – Rovinj, Bakar, Split, and Dubrovnik (Orlić and Pasarić, 2000). In the latter paper it was stressed that the oscillation does not represent the nodal tide, since neither the amplitude nor the phase agree with the theoretical values for the equilibrium nodal tide, but that it may be related to global bidecadal signal. As documented by Mann an Park (1996), this signal manifested itself in the Mediterranean area in low air pressure and high air temperature in the early 1960s and 1980s (i.e. at the time of high sea levels) and high air pressure and low air temperature in the early 1950s, 1970s, and 1990s (i.e. at the time of low sea levels). Moreover, the time of high/low sea levels coincided with the Mediterranean sea temperatures being high/low (White and Cayan, 1998) and the salinities being low/high (Lascaratos, 1989). Tide-gauge measurements performed in the Adriatic after these studies confirmed the existence of bidecadal oscillation. They also pointed to an apparent amplification of the signal. Since it is recorded at all Adriatic stations, the amplifications appears to be a realistic feature that demands an adequate explanation. Obviously, a proper interpretation of the modulation necessitates that the bidecadal variability itself be understood, and this is crucial to differentiating natural climate changes from those due to anthropogenic forcing.

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Stability of Marine Ice Sheets and Grounding Line Modelling

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Marine ice sheets are ice sheets with the bedrock lying below sea level. For marine ice sheets where this bedrock is locally or regionally overdeepened, unstable behaviour of the ice sheet is to be expected, as shown in theoretical approaches by Weertman (1974) and Schoof (2007). These studies also provide analytical solutions of grounding line position as a function of ice flux at the grounding line and show that when stable steady states are to be expected, their solution is unique. In this poster we explore different implementations of grounding line migration that can be integrated into large scale numerical ice sheet models of the Antarctic and Greenland ice sheet. We compared different approximations to the Stokes equations for ice flow in transition zones between an ice sheet and an ice shelf. Results are verified with theoretical work mentioned above. Preliminary results of grounding line migration algorithms in three dimensions are discussed as well.

Dynamics of the Antarctic Ice Sheet: Observations and Potential Instabilities

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The IPCC's Fourth Assessment Report Sea explicitly choose not to include estimates of the sea level rise (SLR) caused by the changing dynamics of ice sheets (e.g., sea level projections for 2090-99 are "model-based range excluding future rapid dynamical changes in ice flow" IPCC 2007 SPM). This decision was made on the justifiable basis that "current models may be inadequate to treat it because of limited resolution and poorly understood processes" (Meehl and others 2007, pp831) and has proven a very effective means of focussing the attention of the international scientific community on this area of uncertainty. In the intervening three years, many national and international programmes have been initiated specifically to address this issue. Examples include large efforts to improve the modelling of ice sheets (e.g., amongst many others the EU's ice2sea and the US' ISICLES programmes), as well as extensive ship-based, airborne and field campaigns to West Antarctica.

The key observations that prompted this activity were made by satellite radar altimeters on the ESA1 and 2 satellites, and have subsequently been extended by ENVISAT as well as the space-borne lidar of ICESAT. A consistent picture has emerged of slight thickening (measured as an increase in surface elevation) of ice in the deep interior of the East Antarctic ice sheet (related to increased snowfall) with higher rates of thinning associated with specific outlet glaciers in both East and West Antarctica (Totten and Cook Glaciers in the former, and Smith, Pine Island and Thwaites Glaciers in the latter). All of these thinning outlet glaciers have in common that they rest on deep troughs well below sea level. More recently, this thinning has been shown to be accelerating and has raised concerns about the stability of the ice sheet in these sectors.

The glaciological community has long been concerned about the way in which floating ice (ice shelves) interacts with grounded ice (ice sheets and their ice streams and outlet glaciers), and the wider implications of this interaction on the stability of marine ice sheets. While many of the earlier analyses were theoretical, the collapse of the Larsen B ice shelf in 2002 presented an excellent natural experiment for testing the importance of the interaction. The surge response of the glaciers draining into the former ice shelf, as well as the lack of such a surge in the glaciers draining into the surviving remnants of the ice shelf, strongly suggests that, at least in some circumstances, the two systems are closely coupled by the transmission of longitudinal stresses. The observation of some delayed thickening, however, suggests response of the grounded glaciers is complex.

The concepts developed in the analysis of the effects of the Larsen B collapse may be more widely applicable to understanding larger systems such as Pine Island and Thwaites Glaciers (PIG and TG) in the Amundsen Sea sector of West Antarctica. A great deal of progress has been made in understanding the sequence of events that could have led to the observed thinning of PIG and the consensus view is that the thinning is a response to changes in PIG's ice shelf. The response is thought to be by two distinct processes. The first is the longitudinal transmission of stresses across the grounding line, which causes additional stress to be accommodated by traction at the ice stream bed and lateral margins causing ice to flow to accelerate. This is instantaneous and triggers a diffusive response which relies on the coupling of ice flow and gravitational driving (specifically ice surface gradient) and has times scales of decades. Strong corroboration of the latter process comes from recent field-based GPS observations of the trunk of PIG. The exact balance between the two processes seems likely to depend on details such as the rheology of the sediment over which PIG flows. Satellite observations of surface elevation change and ice velocity indicate that there was a step increase in velocity in the mid-1990s (preceded by a period of near steady flow extending back to the mid 1970s). They also show that thinning has increased from the mid-1990s to the present by a factor of four. The exact trigger is still uncertain and retreat of the grounding line, retreat of the shelf's calving ice front and thinning of shelf itself (with the associated loss of grounding) have all been observed and remain potential causes. The dynamics of TG appear to be more complicated; thinning and grounding-line retreat are in this case associated with a widening of the ice stream.

Ocean modelling of the circulation within the Amundsen Sea suggests strong variability in the upwelling of the relatively-warm Circumpolar Deep Water (CDW) on to the continental shelf. When forced with atmospheric reanalyses, the upwelling occurs most strongly in the mid 1990s which correlates well with the observed start of PIG's current thinning and grounding line retreat. The ultimate cause of the variability within CDW upwelling remains uncertain, however it is most likely related to the coastal wind fields and regional atmospheric pressure systems in this sector of Antarctica. Recent airborne and ship-based campaigns to PIG and its ice shelf have identified a bedrock ridge cutting across the sub-shelf ocean cavity, which may have implications both for the interaction of CDW with the ice shelf and its melt, and the degree of recent grounding experienced by the PIG system. Exploration of the sub-shelf cavity by the autonomous submersible AUTOSUB confirms the presence of CDW. Modelling of the interaction between CDW and the ice shelf (validated by estimates made from observed ice flux divergence) suggests that the spatial pattern of melt is highly varied with very high rates of melt (~100 m/yr) associated with the deep, steeply-inclined underside of the shelf close to the grounding line. Very little oceanographic data is available for the Amundsen Sea, however on-going campaigns are seeing the development of a long-term ocean monitoring network, several moorings of which have already been established.

Very significant progress has also been made on the theoretical aspects of the coupling between floating and grounded ice. In particular, a robust analytical theory for the dynamics of the grounding zone has emerged. This has prompted a host of numerical studies of the grounding zone using a wide range of models varying from vertically-integrated models of a flowline through 3d first-order shallow ice models to full Stokes-flow models. A new vertically-integrated formulation of the first-order approximation for ice flow also shows great promise in overcoming the limitations of existing simplifications and reducing the demands of the computational-intensive models towards the latter end of this list. Novel new numerical techniques are evolving to deliver the very high resolution thought to be needed to model grounding-line migration (less than 1 km) compared to large size of the overall domain (total area of the ice sheet is ~14 million sq. km). While it is too early to make definitive predictions, it does appear that goal of robust predictions of grounding migration is in sight.

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Towards Coupled Ocean-Ice Shelf-Ice Sheet Modelling of Pine Island Glacier, West Antarctica

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We report initial progress in applying a hybrid ice sheet – ice shelf model to the Pine Island Glacier, West Antarctica. The model employs the scheme proposed by Schoof and Hindmarsh (2010) to reduce the full 3D stress balance to a vertically-integrated, 2D form, whilst retaining the ability to simulate both slow sheet flow (in which vertical shear dominates) and fast stream flow (in which horizontal terms dominate). The work uses a newly developed 1-km resolution dataset for the PIG catchment, based on recent airborne surveys of the area and with bedrock, ice surface and thickness consistent with one another and with the present-day location of the grounding line.

The model is forced with changes in the rate of melt from the underside of the floating ice shelf, which are derived from a 2D model of the interaction between ocean and meltwater-rich plume (Payne and others 2007). Although, the majority of the experiments to be reported use a fixed grounding line location, we conduct some initial experiments where small changes in grounding line location are allowed to occur and feedback into the geometry of the ice stream and, therefore, its flow dynamics.

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Closing the Budget of Global Sea Level Rise: The GRACE Correction for GIA Over the Oceans

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Although it has been understood for some time that significant corrections must be made to satellite altimetry measurements of the ongoing rate of global sea level rise to account for the continuing influence of the variations in Earth's shape due to the last deglaciation event of the Late Quaternary ice-age (Peltier, 2001), it is only very recently that accurate calculations have become available of the equivalent correction that must be applied to the time dependent gravity data being measured by the GRACE satellite system (Peltier, 2009; Peltier and Luthcke, 2009). The measurements being provided by these satellite systems may now be usefully employed to address the issue as to whether we are now in a position to claim that the budget of global sea level rise is closed. The budget itself may be usefully understood in terms of the algebraic relation:

Altimetry (T/P-GIA) = Mass rate (GRACE-GIA) + Steric rate (e.g., Argo floats) (1)

Each of the terms in this relationship is to be understood as representing an average over the global ocean. The two terms on the right hand side of this expression represent, respectively, the contributions to the global rate of sea level rise due to the addition of water mass to the ocean basins by the melting of land ice and that due to the steric effect of the thermal expansion of a fixed mass.

It is also possible to test for closure of the budget by focusing exclusively upon the mass component by comparing the rate at which mass is being lost from the land, due to the disappearance of land ice, to the rate at which mass is accumulating in the oceans. Seen from this perspective, the algebraic incarnation of the closure test takes the form:

Mass rate increase over the oceans (GRACE-GIA) = Mass rate from the land (small ice sheets and glaciers) + Mass rate from the land (great polar ice sheets) (2)

Irrespective of which of these methods one chooses to employ as the basis of the test of sea level budget closure, it will be clear that the GIA corrected GRACE observations play a crucial role. Both of these methodologies have recently been compared in Peltier (2009) with the result that in either case closure is successfully demonstrated within the observational uncertainties. The most important aspect of these analyses concerns the magnitude of the GIA correction to the GRACE inference of the rate at which mass is being added to the global ocean. Table 1 lists the values of this correction (denoted Avg. mass-rate), delivered by the ICE-5G (VM2) model of the glacial isostatic adjustment process for several different assumptions subject to which the calculation is performed. Also listed is the value of the altimetry correction (denoted Avg. dGeoid). These corrections are both listed as an equivalent rate of global sea level rise in mm/yr.

Of utmost importance is the difference between the unfiltered value of the GIA correction for mass-rate based upon the predictions of the ICE-5G (VM2) model and the value that would be predicted if the degree 2 and order 1 Stokes coefficients were eliminated from the calculation.

In this case the magnitude of the correction is reduced by approximately 0.5 mm/yr. Since these Stokes coefficients carry the full influence of the polar wander induced by ice-sheet growth and decay during the Late Quaternary glacial cycle, when we eliminate them from the computation of the GIA correction we are making the same error as advocated in the paper by Mitrovica et al (2005), the critical error in whose analysis has been discussed in Peltier and Luthcke (2009). In Peltier (2009) it is noted that by employing a GIA correction based upon the GIA analyses of Paulson et al (2007), which is itself based upon the flawed analyses of Mitrovica et al. (2005), Leuliette and Millar (2008) have made a similar error of analysis in their own assessment of the sea level budget closure problem. Our analyses are in close accord with those of Cazenave et al. (2008) who have employed the GRACE corrections provided for the ICE-5G (VM2) model listed anew herein. See Figure 1 for an example of the GIA corrected GRACE field over the North American continent which compares ICE-5G with ICE-6G results.

Table 1. The mass-rate correction that must be applied over the oceans to raw GRACE data to correct for the influence of the GIA process associated with the Late Quaternary ice-age cycle of glaciation and deglaciation under the assumption that the last of these 100,000 year cycles ended 4000 years ago. Also listed.is the correction for the altimetry based observations of the net rate of global sea level rise which is denoted by dGeoid in the Table. Results are shown for several different assumptions on the basis of which the calculation has been performed. These include the width of the Gaussian filter applied in the analysis to smooth the data, if any, and whether or not the degree 2 and order Stokes coefficients are retained in the analysis.

Gaussian half-widths	Coefficients excluded	Maximum degree and order	Range of latitude	Avg. mass-rate over the oceans	Avg. dGeoid over the oceans
No filter	none	120	+/- 90 degrees	-1.80 mm/yr	-0.30 mm/yr
400 km	none	120	+/- 90 degrees	-1.65 mm/yr	-0.29 mm/yr
No filter	(2,1)	120	+/- 90 degrees	-1.32 mm/yr	-0.26 mm/yr
400 km	(2,1)	120	+/- 90 degrees	-1.17 mm/yr	-0.26 mm/yr

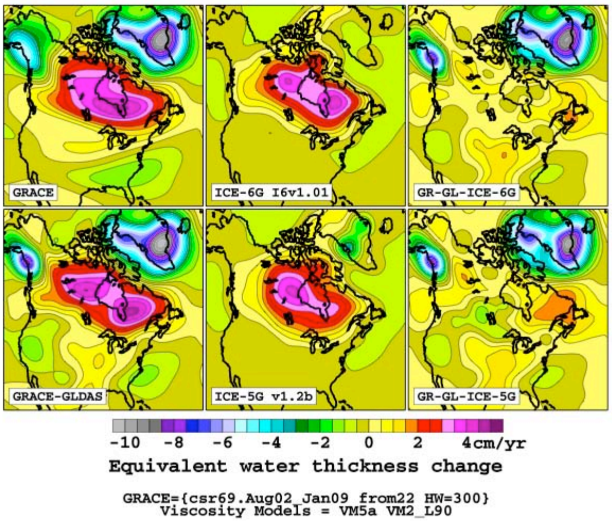

Figure 1. Shows the raw GRACE data over North America (GRACE) using Stokes coefficients from degree 2 and order 2 up as well as the GRACE field corrected for Hydrology (GRACE-GLDAS). The predicted GIA corrections are also shown for the ICE-5G and ICE-6G model of the global GIA process as well as the differences between the hydrology corrected GRACE data and the GIA prediction.

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Glacier Contributions to Sea Level Rise: Past, Present and Future

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As of 2006, the date of the last globally comprehensive compilation of sources of eustatic sea level rise, glaciers and ice caps, exclusive of the Greenland and Antarctic Ice Sheets, contributed approximately 62% of land ice contributions to sea level. In the subsequent 4 years, the contributions from Greenland and Antarctica have increased significantly, and while the corresponding changes in glacier and ice cap contributions are unmeasured, it is estimated that their contribution in 2010 is at least 46% of the global present-day total rate of eustatic sea level rise. I review the current best knowledge of glacier and ice cap area and volume, rates of mass loss, the geographic distribution of those losses, and the potential future effects of ice dynamics and declines in remaining source volumes. I present simple near-term extrapolations which provide estimates of the contribution of glaciers and ice caps relative to Greenland and Antarctica over the next ca. 15 years, and discuss the increased uncertainty in future sea level rise due to unmeasured glacier and ice cap losses.

Oceanographic Evidence of Climate Change in Ecuador

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The purpose of the project "Oceanographic evidence of climate change in Ecuador" is to search for relevant information on the sea level variation and provide updated information on changes and trends of air temperature and sea temperature, in order to raise the attention of the society and decision-makers on the existing problem.

The main source of information for this study is supported at the national oceanographic data center (CENDOC). This center is a department that stores and manages the information generated by INOCAR and by any other institution or organization that collects oceanographic data in the Ecuadorian marine territory.

Being the main criterion to work with continuous and homogeneous records and in order to meet the specific objectives of the study we had to discriminate some records because their short time length did not allow a correct analysis according to the statistic standards applied for oceanographic data. Table 1 shows the selected locations as well as the variables, and the analysis done on each station.

Each series was fitted with a first degree (linear regression) polynomial. At first it was used the entire study period and then only from 1995 until 2008. These two comparisons were necessary to make sure that the variations were not part of an inter-decadal cycle, considering that the analyzed data is only from the past 13 years.

Interdecadadales variations were calculated according to the GEOPHYSICAL RESEARCH methodology, through a double filter moving average of 7 series of annual anomalies and inter-annual variations calculated as the difference between the series of annual anomalies and inter-decadal variation.

The sea level was analyzed in three of the seven locations, finding an increase of 6.6 cm. for Puerto Bolívar, and a decrease of 3.3 and 1.88 cm. in Esmeraldas and La Libertad respectively.

For La Libertad, from 1995 until the end of 2008 sea level has risen 7.80 cm and for Puerto Bolívar 5.20 cm. Esmeraldas shows an increase of 1.20 °C on sea surface temperature, which is not coherent with the sea level, that shows a decrease of 0.52 cm.

The longest record for sea-level that Ecuador has is in La Libertad. This data shows a inter-decadal oscillation with a negative trend. However, after the years 1989 - 1990 it shows a positive trend reflected in a 7.80 cm. rise of the sea-level from 1995 to 2008. If it continues to oscillate in this way, it is expected that the increase will continue until 2015 at a rate of 6 mm. per year.

Table 1. Stations, variables, and study periods

	Air Temperature	Maximum Temperature	Minimum Temperature	Sea Temperature	Sea Level
San Lorenzo	1975-2008	1975-2008	1975-2008	1975-2008	
Esmeraldas	1975-2008	1975-2008	1975-2008	1975-2008	1980-2008
Manta	1975-2008	1975-2008	1975-2008	1975-2008	
La Libertad	1975-2008	1975-2008	1975-2008	1975-2008	1948-2008
Guayaquil	1975-2008	1975-2008	1975-2008		
Puna	1977-2008	1977-2008	1977-2008	1984-2008	
Pto Bolívar	1975-2008	1975-2008	1975-2008	1975-2008	1977-2008

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Contribution of the Cryosphere in China to Sea Level Rise

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Cryosphere distributes widely in China. At the present, there are 46377 glaciers with a total area of 59425 km^2 and a volume of about 5600 km^3. The permafrost region is about 2.2 × 106 km^2 (1.4 × 106 km^2 in the Tibetan Plateau). Snow cover lasts longer than 60 days over about 4 × 106 km^2. Other cryospheric components such as sea, river and lake ice are relatively much less (Ding and Ren, 2010).

On global scale, according to IPCC 2007 report, the area of total glaciers and ice caps is estimated to be 0.51~0.54 × 106 km^2 and the volume has a rather large estimation range of 0.05 to 0.13 ×106 km^3, with a potential sea level rise of 0.15 to 0.37 m. Numerous researches show that glaciers in the world are in regression and the melting water is a major part of cryospheric contribution to sea level rise in the past decades, especially since 1990s the glacier melting seems to be accelerated in many regions. During the period of 1993-2003, contribution of glaciers and ice caps in the world to sea level rise is about 0.8 mm per year from IPCC report. The glaciers in China have a 0.014 m of potential sea level rise. It is reported that more than eighty percent of glaciers in China have been in retreat since 1970s. The glacier melting water is estimated to be 630 × 108 m^3 per year during 1961-2006, and about 800 × 108 m^3 per year during 2001-2006 (Ye Baisheng, personal communication). Taking this figure, melting of glaciers in China is contributing the sea level rise of 0.215 mm per year recently.

The permafrost temperature rise and the active layer thickening have been observed widely in the Tibetan Plateau as well as in the Tien Shan and other mountains. Ice volume contained in the Tibetan Plateau permafrost is about 9500 km^3 and the permafrost melting water is estimated to be 50~110 × 108 m^3 per year (Zhao et al., 2010). Since the permafrost melting water does not drain into rivers directly and so it is difficult to assess its contribution to sea level rise. Even if the water has supplied the surface runoff completely, its contribution to sea level rise should be less than 0.03 mm per year.

Due to the monsoon influence, snow cover in China has an increase trend in the past decades (Ding and Ren, 2010), contrary to the decrease in snow cover over the whole north hemisphere (IPCC, 2007). The annual average of snow cover water equivalent is 300-400 × 108 m^3 since 1990s, but it is generally regarded to be negligible to sea level rise since it is from seasonal precipitation.

To sum up, total contribution to sea level rise from the cryosphere in China is between 0.2 and 0.3 mm per year at present and in near future.

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Dynamics of the Greenland Ice Sheet: Observations and Potential Instabilities

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Both the Greenland and Antarctic ice sheets are losing mass at present and their mass loss is increasing with time. As a result, these ice sheets are major contributors to present-day sea level rise. At their current rate of mass loss increase per year, these ice sheets are already on pace for a meter level sea level rise per century, well in advance of model forecasts. In this presentation, we are focusing on Greenland, but physical processes and theoretical aspects relevant to Greenland are equally relevant to Antarctica, tidewater glacier systems and even ice caps and surrounding icefields. Glaciers and ice sheets interact with the ocean, the atmosphere and the lithosphere and as a result may develop instabilities. The most aggressive and unstable end member of the ocean-atmosphere-ice-lithosphere system is the marine ice sheet/ice shelf system, which entrained large sectors of ice sheets to retreat rapidly and create spikes in sea level change in prior times.

In Greenland, detailed and thorough observations collected over the last two decades have revealed that the ice sheet mass balance is controlled by the evolution of ice at the periphery of the ice sheet, roughly equally between changes in surface mass balance and changes in surface flow speed. Changes in surface mass balance are dominated by an increase in surface runoff that is a direct consequence of a warming climate. Changes in surface speed are associated with glacier instabilities. Driving causes for these glacier accelerations are changes taking place in the glacier frontal regions, which for the vast majority are in contact with the ocean. The increase in surface melt did not have much of a direct role – via enhanced basal lubrication – in glacier speed up. Ice-shelf collapse in the northern and western sectors did trigger glacier speed up as expected, but the response is strongly modulated by the geographic context. What was not expected is the major role of the ocean for tidewater glacier systems, i.e. glaciers that do not develop into a floating ice shelf but calve directly into the ocean at their marine termini. These glaciers control the largest share of the ice discharge from Greenland. Observations have shown that the rates of submarine melting of these glaciers are one order magnitude larger than at the surface and considerably larger than underneath ice shelves. Southern tidewater glaciers sped up when brought in contact with warmer than usual ocean waters in the glacial fjords. The glacier response has been overwhelming, unanticipated and complex since glacier behavior varies significantly from one fjord to the next. At present, most glaciers affected by acceleration – with some bouts of deceleration - except for Jakobshavn Isbrae, are resting on beds that raise quickly above sea level inland, hence not the typical case of an unstable system. As glacier instabilities develop farther north, in the marine-based sectors of the ice sheet, more significant changes in ice sheet mass balance are to be expected in decades to come. Predicting these changes requires full accountancy of the glacier physics, more detailed basic observations of their settings and make up, and a realistic coupling of numerical ice sheet models with ocean and atmospheric forcing.

On the Role of Ice-Ocean Interactions in Ice Sheet Mass Balance

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Many - if not all - large glaciers in Greenland terminate in the ocean and qualify as tidewater glaciers; and nearly all major Antarctic glaciers terminate in the ocean and extend into floating ice shelves. As ice enters in contact with the ocean at the grounding line – where ice detaches from the bed and becomes afloat – it interacts vigorously with the ocean waters and melts. Unlike melting under the grounded ice sheet, processes in the submerged parts of glaciers are governed by the transport of ocean heat and by the seawater freezing temperature dependence on pressure. This allows sensible heat to be obtained from the cold, dense shelf waters resulting from sea-ice formation, as well as warm deep water than intrudes onto the continental shelf and flows into ice shelf cavities. Bottom melting freshens and cools the seawater, adding buoyancy that drives upwelling as the ice shoals seaward. In the case of tidewater glaciers, subglacial discharge at the grounding line procures an additional source of buoyancy that ventilates the ocean cavity and entrains additional heat onto the calving face of the glaciers.

The floating extension and submarine fronts of glaciers exert an enormous mechanical control on ice flow dynamics that has been known since the early 1970s but was longer in dispute until we had irrefutable satellite observation to test it. This was the case of the aftermath of the collapse of Larsen B ice shelf in the Antarctic Peninsula: the glaciers upstream of the ice shelf accelerated by a factor 3 to 8 in response to ice shelf collapse- and are still flowing at these fast speeds today, 8 years after the collapse. In the case of tidewater glaciers, the most likely cause for the speed up of glaciers in southern Greenland and elsewhere is the presence of warmer ocean temperatures than normal near the glacier fronts (Holland et al., 2008; Rignot et al., 2010; Straneo et al., 2010). Even though this effect was expected in Antarctica; it was not expected in Greenland. In order to explain or predict glacier evolution, and therefore ice sheet mass balance at large and contribution to sea level worldwide, it is essential to have a good understanding of the evolution of submarine ice.

On floating ice shelves, submarine melting ranges from a fen tens of cm/yr to a few tens of meters per year (Rignot and Jacobs, 2002). On tidewater glaciers, submarine melt rates in Greenland are in the range of meters per day in the summer, and several hundred meters per year over the entire year, with minimal activity during the winter months. These rates are very high and dominate the mass balance of floating ice on ice shelves or control half of the mass ablation of tidewater glaciers when no floating ice shelf exists. Ice-ocean interactions are therefore a fundamental control on ice mass balance. At present, we do not know how to predict these rates, they depend on ocean temperature, ocean circulation, the shape of sub-ice shelf cavities and fjord depths and other parameters that have not been studied in much details.

If the IPCC AR5 wants to put together predictions of ice sheet evolution in a warming climate to constrain sea level rise, it is clearly fundamental that we need to improve our understanding of the evolution of submarine ice. In both Greenland and Antarctica, recent research indicates that the major control on glacier evolution, not just one control, is the ocean. At present, we do not know how to constrain ocean water temperatures, heat fluxes beneath ice shelves, and submarine melt rates because sub-ice-shelf cavities are poorly known or unmapped, fjord depths are poorly known, ocean temperatures in glacial fjords and along the grounding line of ice shelves are virtually unknown, and the processes of ice-ocean interactions are not well constrained by models and observations. Progress is being made by the survey of ice-shelf cavities and fjord depth using airborne gravity, and by the coupling of ice sheet models with global ocean models, but until realistic results are obtained from ice-ocean interaction models, predictions of ice sheet evolution will have to be taken with a grain a salt (sic).

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Next Century Sea Level Contribution of Antarctica in a Worst Case Scenario of Ice-Marginal Changes

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Last IPCC report outlines that the contribution of large ice sheets is a major source of uncertainty when attempting to forecast the future sea level rise. Recent contribution to sea level rise induced by acceleration of outlet glaciers in Greenland and Antarctica is now well documented and modelling studies are conducted to estimate their related contribution in the future.

However, a possible retreat of the grounding line is another aspect of ice dynamics that is seldom dealt with. A few observations of the present retreat are available but sea level rise projection induced by such a process all around Antarctica has not been established yet. The main reason of this omission is that grounding line treatment is a difficult task both from theoretical and numerical point of view. Significant improvements have been recently done and tend to confirm the old hypothesis that marine ice-sheets resting on an upward sloping bed cannot find a steady position.

Simulating this process is still an unsolved question with a 3D global ice sheet model. To bypass this difficulty we follow a simple approach: i) regions that are subject to grounding line retreat are determined according to topographical consideration. ii) On the basis of current observations and 2D numerical modelling (Durand et al., 2009) we assume a maximum grounding line retreat rate of 1 km/year to draw a worst case retreat scenario iii) this scenario is prescribed as lateral boundary condition to a 3D ice sheet model (GRISLI, Ritz et al., 2001) that solves evolution of the whole ice sheet (here with a resolution of 15 km). iv) sensitivity experiments are performed to assess the additional impact of removing fringing ice shelves that presently exert a back force limiting ice stream velocity. On the century time scale, we estimate that such experiments provide a realistic upper bound of the Antarctic contribution to sea level rise due to ice-marginal changes that could be due for instance to oceanic forcing.

Simulations where we prescribe the grounding line retreat alone lead to a contribution of about 50 cm equivalent sea level rise at the end of the first century (after the beginning of the perturbation). Pure geometric effect is responsible for 30 cm and 20 cm are due to inland propagation of the thinning. Adding all the processes (grounding line retreat and ice shelves removal) the total contribution reaches 75 cm equivalent sea level rise in one century.

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Previous Sea Level Rise Estimates and Future Plans: An Overview of Sea Level Rise Activities at Meteo-France / CNRM-GAME

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Sea level rise is a major consequence of global warming, which threatens many low-lying, densely populated coastal regions of the world. Studying future coastal land losses at a given location is a challenging task. Doing so for a particular coastal region generally requires to downscale regional sea level rise spatial patterns, and to have sufficient data about local coastal geomorphology and topography. In this paper, we will focus on modelled large scale sea level rise spatial patterns.

The main contributor to sea level spatial variability is thermosteric ocean expansion, due to the non uniform warming of oceans. However the post-glacial rebound and the water input to the oceans, due to the melting of ice sheets also contribute to shaping this spatial variability.

For a given emission scenario, the thermosteric component of global sea level rise estimated by coupled climate models shows relatively little spread, but there is little or no agreement between models in terms of spatial patterns (IPCC, 2007). This lack of agreement can be attributed to the differences in simulated ocean warming spatial patterns. More over, observational estimates of total sea level rise since 1900, at about 0.2 m are not reproduced by models over the same period. For example, the CNRM-CM3 model (based on OPA8 rigid lid ocean model coupled with Arpege-Climat atmosphere model, about 2° resolution in longitude / latitude), which was one of the CMIP3[1] / IPCC-AR4 models simulated a thermosteric component of sea level rise as small as 0.05m since 1900. This suggests that the projected values of sea level rise for 2100 may be underestimated. However, even if the hindcasted sea level rise was clearly underestimated by CNRM-CM3, the same model simulated regional thermosteric sea level rise spatial patterns that were comparable to reconstructions from tide gauges and satellite altimetry over the period 1950-2003.

In order to contribute to CMIP5 and the IPCC fifth assessment report, CNRM-CM5 was developed in collaboration with Cerfacs (Toulouse). This model has a horizontal resolution of about 1° and now includes the most recent versions of NEMO (free surface) ocean model and Arpege-Climat. Sea level rise patterns are now computed on line, taking into account the contributions of ocean dynamics and the direct impact of the surface net water flux. No historical or future climate simulations were run yet with this new model, but it is hoped that these recent developments will yield more realistic hindcasts of sea level changes spatial patterns. Ice sheet models representing the Greenland and Antarctic ice caps (GRISLI, 15km horizontal resolution) will be implemented in CNRM-CM5 in 2011, to account for global warming-induced meltwater input to the ocean.

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[1] Coupled Models Intercomparison Project Phase 3

Faster Ice Flow in Southwest Greenland During Years of Low Melting

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Fluctuations in surface melting are known to affect the speed of glaciers and ice sheets (Joughin et al., 2008; Shepherd et al., 2008; Van de Wal et al., 2008; Palmer et al., 2009; Bartholomew et al., 2010; Das et al., 2008; Zwally et al., 2007), but their impact on the Greenland Ice Sheet (GrIS) in a warming climate remains uncertain (Meehl et al., 2007). While some studies suggest that greater melting produces greater ice acceleration (Zwally et al., 2007; Parizek and. Alley, 2004) other observations have identified a long-term decrease in Greenland's flow despite increased melting (Van de Wal et al., 2008). Here we combine a multi-year dataset of satellite observations and modelled runoff to investigate the extent to which inter-annual fluctuations in the degree of surface melting modulate ice flow in an ice-marginal area in southwest Greenland. In addition to seasonal glacier velocity cycles (Joughin et al., 2008; Shepherd et al., 2008; Van de Wal et al., 2008; Palmer et al., 2009; Bartholomew et al., 2010; Zwally et al., 2007) we identify an altitudinal progression in the onset of cyclicity (Bartholomew et al., 2010) and large inter-annual variations in ice motion. On years of high melting, the average speedup during the latter half of summer was ~50 % lower and the period of peak velocity was ~50 days shorter than on years of lower melting. We interpret these differences to reflect faster development of efficient subglacial drainage in warmer melt-seasons, an effect observed at mountain glaciers (Bartholomaus et al., 2008; Truffer et al., 2005; Bingham et al., 2003; Bingham et al., 2006). Our observations support arguments (Van de Wal et al., 2008; Truffer et al., 2005; Price et al., 2008) that assessments of the impact of melt induced acceleration on Greenland's flow should account for the development of subglacial drainage, and suggest that increased surface meltwater input to the bed could even lead to reduced ice flow.

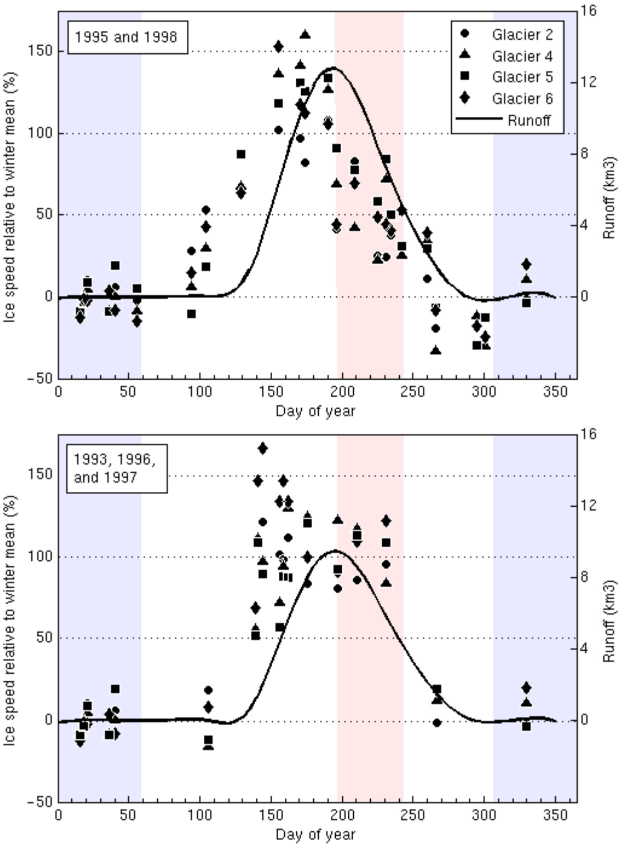

Figure 1. Ice velocity recorded during years of high (top) and low (bottom) surface melting, relative to the wintertime mean. The ice velocities are mean values of the 500-600 masl elevation band on glaciers 2, 4, and 6 and the 400-500 masl elevation band on glacier 5. The red and blue bands define the periods used to calculate the late summer speedup and average winter velocity, respectively. Data from all five years were included when calculating the average winter velocity.. The median and maximum errors of the velocity dataset are 17 and 35 m/year, respectively. The curves represent averages of the 1995 and 1998 (top) and 1993, 1996, and 1997 (bottom) monthly runoff estimates.

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Recent Progress in Holocene Glacier Fluctuations Studies: Questions Relevant to the IPCC

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The Holocene mountain glacier variations in comparison with the modern glacier sizes were considered in the IPCC AR4 (Chapter 6 "Paleoclimate") in connection with the respective climatic forcings. The general conclusion was: "Glaciers of several mountain regions of the Northern Hemisphere retreated in response to early-to mid-Holocene warming, and were smaller than at the end of 20th century, or were even absent. The present day near-global retreat of mountain glaciers cannot be attributed to the same natural causes: the decrease of summer insolation during the past few millennia in the Northern Hemisphere should be favorable to the growth of the glaciers". This conclusion was in agreement with most of other findings reported in AR4, however it was clear that many specific questions remained unresolved. The main limitation for more comprehensive conclusions was the lack of accurate detailed glacial chronologies, especially in the Southern Hemisphere and in the tropics.

Since the AR4 surprisingly large number of papers on this topic had appeared (e.g., Special Issues: Global and Planetary Change, v. 60, 2007, "Historical and Holocene Glacier-Climate Variations", and Quaternary Science Review, v. 28, 2009, "Holocene and Latest Pleistocene Alpine Glacier Fluctuations: A Global Perspective"). Most of the recently updated reconstructions are of multi-proxy origin and are based both on the discontinuous records (age of moraines) and continuous chronologies of lake sediment properties. They provide a better ground to compare the individual chronologies and to estimate the spatial and temporal coherence between them at the regional and global level.

The mayor progress in the field occurred due to the application of relatively new technique of dating moraines by cosmogenic isotopes. 10Be was the most efficient for this purpose (Schaefer et al., 2009; Glasser et al., 2009; Licciardi, 2009). In contrast to the radiocarbon-based glacial chronologies which are able to provide only the minimum or maximum limiting dates of moraines and those dates are normally identified for the glaciers located in different valleys, the 10Be-based series allow the dating of moraine landforms themselves. Most of these new or improved chronologies are coming from the tropical areas.

The new data confirm the opposite long-term trends in glacier variations in the Southern and Northern Hemispheres being in accordance with the summer insolation trends in both hemispheres. The results of the analyses of decadal to multi-centennial patterns of glacier variations and potential climatic forcings of these variations are not yet conclusive. Wanner et al. (2008) did not find a worldwide coincidence between solar irradiance minima, tropical volcanic eruptions and decadal to multi-century scale cooling events accompanied by advances of mountain glaciers during the last 6 ka. A certain correlation has been shown between the Bond events and Holocene glacier advances and retreats in Scandinavia (Matthews et al., 2005) and the European Alps (Holzhauser et al., 2005), though this coherence is not proved at the global scale and no comprehensive mechanism for such a correlation is suggested.

In some regions such as Sweden (Karlen and Kuylenstierna, 1996), Alaska (Wiles et al., 2007), the Canadian Rockies (Luckman and Wilson, 2005) and the Alps (Holzhauser et al., 2005), solar irradiation minima roughly coincided with increasing glacier lengths during the past few millennia. Furthermore a certain correspondence exists in the timing of major glacier advances at the interregional level for instance in the Alps (Holzhauser et al., 2005), Alaska (Wiles et al., 2009) and Southern Tibet (Yang et al., 2007) during the last two millennia: the advances in these regions occurred around AD 200, 400, 600, 800–900, 1100, 1300 and in 17 though 19 centuries. The synchroniety and quasi-regularity (quasi- 200-years long cycles) imply a potential common external factor forcing the glacier growth in all these three remote regions. Wanner et al. (2008) also identified the 200-years spectral peak (along with the others 500, 900, 1500 years long) in the climatic proxies in the last 6 ka. However all those peaks are statistically insignificant.

Some researchers argue that many glaciers now are already less extensive than they have been throughout the Holocene (Canadian Rockies - Koch et al., 2004) or at least in the Neoglacial period (Quelccaya – Thompson et al., 2006, western Scandinavia - Bakke et al., 2007). In other regions (e.g., in the Alps) the equilibrium line altitude in the Early and Mid Holocene was 220 m higher than in 1960-1985 (equivalent to the summers warming by 1.8ºC assuming unchanged precipitation) (Joerin et al., 2008). However one has the bear in mind that the adjustment of glacier tongues by retreat lags ongoing rapid atmospheric warming by years to several decades.

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Ice Sheet Evolution and Sea-level Changes in Southern Greenland: A Comparison Between a Best-Fitted Glacial-Isostatic Adjustment Model and New Sea-Level Observations from the Inner Bredefjord Area, Southern Greenland

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Until recently there have only been few relative sea-level observations in southern Greenland. As a consequence the glacial history and isostatic adjustment are poorly constrained. We have used glacial isostatic adjustment models to determine the ice sheet evolution in southern Greenland from the LGM until the present. Isolation and transgression sequences from 0-14,000 cal. yr BP from the Nanortalik (Sparrenbom et al., 2006a) and the Qaqortoq (Sparrenbom et al., 2006b) areas are used to constrain the different ice-model scenarios tested and recently new sea-level observations from the Inner Bredefjord area has been incorporate for a comparison. Our studies from the Nanortalik and Qaqortoq areas show an ice sheet extending to the shelf edge from 26,500 cal. yr BP until 22,000 cal. yr BP, followed by rapid retreat (Sparrenbom, 2006). By 12,000 cal. yr BP, the ice margin was inland of the present-day coast and by 10,500 it had reached the present margin. The ice sheet was smaller than at present from 10,500 cal. yr BP and reached a minimum of 30 km inland of the present day margin at 9000 cal. yr BP. The new sea-level observations from the Inner Bredefjord area (Tasiusaq) shows that the relative sea-level fall in the early Holocene was rapid with a regression of more than 26 m between c. 9000 to 8000 cal. yr BP (almost 3 cm/yr). Between c. 8000 cal. yr BP and the present day, the sea level was lower than at present and sea level in the area reached its lowest level, below – 4 m a.h a t., sometime between 7000 and 2000 cal. yr BP. The fast ice regression indicated by this new data in the early Holocene confirms the best fitted ice model scenario of Sparrenbom (2006). The transgression in the Tasiusaq area started around 4000 cal. yr BP when the mid-Holocene climate deterioration had set in and the Greenland Ice Sheet (GIS) had started its re-advance.

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Influence of Ocean Circulation Changes on Sea-Level: Observations, Modelling and Uncertainties

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The impact of sea level variations on mankind depends fundamentally on regional or local sea level conditions impacting nations shore lines. It is therefore that regional and local changes in sea level and changes in storm surges are of larger societal concern and of larger importance for coastal protection, than global estimate of sea level changes. In fact, regional sea level changes can be of opposite sign to global estimates due to changes in the ocean flow field and associated mass redistribution. Understanding the large-scale variations in sea level arising from changes in ocean dynamics on climate time scales, understanding the role of the changing ocean circulation in shaping regional and local sea level and comparing related amplitudes with changes expected from changes of the goid or post glacial adjustment is therefore of importance for understanding future sea level variations and their coastal consequences.

Sea surface height can be changes through changes in wind forcing, as well as changes in the oceans content of heat and freshwater content, or changes in its mean mass. Any change of one component locally has to be compensated and communicated globally via planetary waves, changes in the flow field and associated changes in advective processes or mixing. As such it is the planetary waves and associated changes in the flow field that will communicate an adjustment of sea level to regional and local addition of freshwater originating from melting polar ice shields. Time scales involved in the associated dynamical adjustment can be long, lasting for many decades or even several centuries. Details of that adjustment are not clear quantitatively, though, because we will have to learn how the ocean reacts to and distributes locally injected freshwater.

Today we can observe changes in sea level using satellite observations and interpret those in terms of forcing functions and ocean dynamics. However, a clearer picture about underlying changes in the flow field and the role which changing ocean transports play in this context can only emerge from additional information provided by ocean circulation models or coupled climate models. Moreover, both have uncertainties as have ocean observations, making a joint analysis and interpretation mandatory.

The talk will review the state of the art observations and modeling of sea level, will review the impact of ocean dynamics on regional and local sea level in comparison to static geodetic adjustments and will discuss uncertainties in existing projections of regional sea level. In essence, we need to build into our climate models the time history of dynamical changes of sea level arising from freshwater sources at various locations spread across the globe, need to build in the local static adjustments to changes in ice mass and need to consider relative local changes in sea level pressure if where to quantitatively project regional and local sea level conditions into the future.

Response of the Coupled Ocean-Atmosphere System to Greenland Ice Melting

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Numerical simulations suggest that an increased melting of the Greenland ice sheet leads to a dynamical sea level response on local and regional scale. Our results from an ocean-only simulation suggest that the largest baroclinic SSH increase in response to Greenland ice melting should be observed along the coastal Atlantic, notably the west coast, due to a response of the Atlantic circulation. However, Mitrovica et al. (2001) suggest that because a melting of the Greenland ice sheet will reduce the height of the geoid in the vicinity of Greenland, this consequently will lower sea level around the regions of ice melting (see also Tamisea et al., 2001). The same holds for any other polar ice sheet. A quantitative projection of sea level therefore needs to take into account the dynamical response of the ocean to enhanced freshwater forcing and respective regional variations of sea level as well as static changes of sea level due to variations in the geoid. Moreover, coupled model simulations suggest that response of the global ocean to enhanced polar freshwater forcing includes also a pathway through the atmosphere, which includes fast reactions, e.g., of the Pacific through perturbed atmospheric fields.

In more detail, increased freshwater runoff from Greenland results in a basin-wide baroclinic response of the North Atlantic on timescales of a few years, communicated via boundary waves, equatorial Kelvin waves, and westward propagating Rossby waves. In particular, the modified ocean dynamics and thermodynamics lead to a depression in the central North and South Atlantic that would not be expected from linear wave dynamics. Other parts of the world ocean experience a much slower adjustment in response to Greenland freshwater forcing, communicated via planetary waves, but also involving advective/diffusive processes, especially in the Southern Ocean. Timescales for a first response of the Atlantic are just a few years in the subpolar North Atlantic and 5–10 years for the Atlantic and global ocean. However, a complete adjustment of the Pacific might take as much as 500 years (Cessi et al., 2004).

Advective processes and air-sea interaction appear to be important elements of the long-term adjustment of the global ocean to Greenland freshwater forcing. In particular, changes in the oceans heat content due to modified air-sea interactions modify the sea level of the central basin of the North Atlantic and the feedback with the circulation then leads to a reduced MOC strength and associated positive southward heat transport anomalies in the Atlantic Ocean. This suggests that the oceans adjustment to anomalous freshwater forcing from melting polar ice caps is a coupled ocean-atmosphere problem and needs to be studied using a fully coupled model, similar to what was started by Stouffer et al. (2006). Preliminary results using a coupled model show a comparable response to Greenland freshwater forcing in the Atlantic Ocean. However, the Pacific shows also a quick response due to changed atmospheric fields. A tele-connection through the atmosphere therefore might need to be considered as well. Details have yet to be analyzed, though (Agarwale et al., 2010).

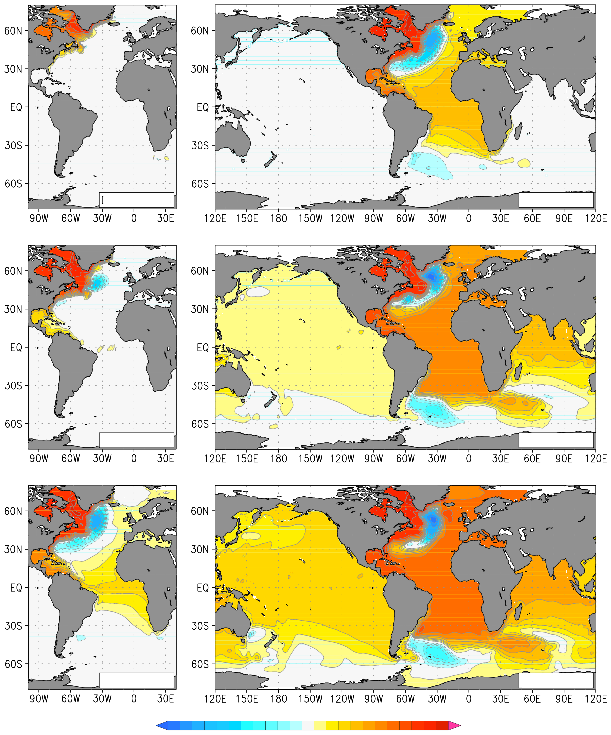

Figure1. December-mean anomalies of SSH as they result from enhanced Greenland freshwater forcing. (left) SSH anomalies for the Atlantic from the years 1, 3, and 6. (right) Similar fields, but globally and for the years 10, 30, and 50 (from Stammer, 2008).

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Greenland Mass Balance: Observations, Modelling and Uncertainties

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The mean surface mass balance (SMB), based on four 50-year records, is 354 Gt/y with a range between estimates of 54%. This is on the order of magnitude of the standard deviation of the interannual variability, which ranges from 62 Gt/y to 124 Gt/y. Since the mid-1990s, runoff has increased significantly with only a modest change in accumulation, resulting in a reduction in the SMB of around ~200 Gt over the last 13 years. 2007 had the lowest SMB of any year in the 50-year time series. Significant differences exist between the various estimates of the components of the SMB derived from numerical modeling and downscaling of climate re-analysis data. The differences suggest that mass budget calculations may have been seriously hindered by uncertainties in the SMB in the past. The most recent mass budget calculation show good agreement with results from independent satellite observations.

Much of the ice loss from the Greenland Ice Sheet occurs by ice discharge into the surrounding ocean. This has been estimated at 50% of the mass loss on average over the last ~50 years, but recently large variability in the flow of many large outlet glaciers has been documented. The temporal variability of Greenland's ice mass balance has a large contribution from variability of flow in its outlet glaciers. Observations during the past decade have shown that ice discharge can increase by a factor of two within a few years and, in some cases at least, that this can also be reversed. These changes are coincident with observations of warming in the ocean and atmosphere, as well as the disappearance of near-coastal sea ice. While the general mechanisms of fast flow are reasonably well understood, the necessary tools for predicting future behavior have not been developed. This is primarily due to a lack of understanding of the ice-ocean coupling and the role of surface water in determining the rates of ice flow.

The total mass balance of the ice sheet (i.e., the sum of surface mass balance and ice discharge) was exceptionally difficult to determine prior to the development of the present suite of observational and analysis techniques. While it is clear from the spread of published results that estimation remains a challenge for these techniques, it is important to note that nearly all the approaches show very similar trends, indicating clearly that the Greenland Ice Sheet is losing significant mass, and has been doing so at an accelerating rate over the past ten years. This conclusion is supported by all approaches sensitive to the ice margins: (1) the change in ice discharge from outlet glaciers combined with increasingly negative surface mass balance; (2) surface lowering in outlet glaciers measured directly by laser altimeters; and (3) the reduction in the mass of the ice sheet measured by the GRACE satellite gravity mission. The challenge of more accurately determining the present and future rate of mass change of the Greenland Ice Sheet, by reducing the uncertainties inherent in the different approaches, will require improvements in measurements, more consistent and complete observational time series, better analysis schemes, and an improved understanding of the physical processes involved in recent rapid changes.

Fingerprints in Regional Sea-Level Variations

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Understanding the spatial variability in observed sea level change is an essential step towards assessing the societal importance of future global sea-level rise estimates. One of the many processes that contribute to the regional variations of sea level is the non-uniform redistribution of the mass of fresh water entering the oceans from glaciers and ice sheets. The changes to gravity and crustal motion cause a relative sea-level fall near the melting ice sheets and a larger-than-average rise in the far field. This process is frequently referred to as "fingerprinting" or self-attraction and loading (SAL). If the spatial distribution of the mass loss is known, then each source produces a pattern of sea level change from the SAL effect that scales with the amount of mass loss. Mitrovica et al., 2001, used these patterns with a select set of tide gauge records to estimate the long-term mass loss from Greenland. The results showed that SAL provides a possible explanation for the lower-than-average sea level rise rates observed across Europe. Subsequent studies using increased numbers of tide gauges (Plag, 2006; Wake et al., 2006; Marcos and Tsimplis, 2007), or careful analysis of individual tide-gauge records (Douglas, 2008), have not produced a consistent set of mass-loss estimates.

Many other processes (steric and atmospheric effects, currents, hydrology, tectonics, etc.) also contribute to the spatial variability of sea level, which makes using these fingerprints to extract past meltwater contributions more difficult. For example, the interannual variability of the water fluxes into the ocean (evaporation, precipitation, and runoff) is typically at least a factor of two larger than observed mass-loss rates (Ponte et al., 2010). Analysis of altimetry data shows that, in many regions, the derived trends at a given point are not statistically significant (Hughes and Williams, 2010). Finally, these analyses typically assume that the mass loss is a simple trend, whereas some observations, such as glacier mass loss, indicate large interannual variability.

However, there are several situations where SAL effects become a larger component of the total signal. For example, in the near-field of the melting glaciers, SAL effects become as large as the trends observed from tide gauge and altimetry data (Ponte et al., 2010). In addition, many processes that impact sea level are effectively reduced in bottom-pressure data. However, the impact of SAL remains the same (Tamisiea et al., 2010). Thus, SAL is a relatively more important component of the total variation (Vinogradova et al., 2010), and bottom pressure may serve as a better observation set for monitoring the mass contribution to sea-level rise. In addition, it is important to remember that these patterns are a well-understood cause of regional variability, and thus are useful in data analysis and future predictions. For example, we can address the regional sea-level change caused by SAL effects for certain end-case scenarios, such as the collapse of the West Antarctic Ice Sheet (Mitrovica et al., 2009; Bamber et al., 2009; Gomez et al., 2010).

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Mean Sea Level Rises in the Gulf of Thailand

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Long-term rates (1940-2004) of sea level changes as determined from annual-average of four tide gauge stations reveals that in the Gulf of Thailand mean sea levels are rising significantly faster than global average rates. Inter-seismic uplifts detected from precise GPS measurements are used to correct the apparent rates from tide gauges, yielding absolute long-term trends at 4.0 mm/yr in the northern part of the Gulf. Along the western coastline, the average rate is 2.9 mm/yr. Post-2004 tidal data are not included in our study due to unknown co-seismic jump and largely-unresolved post-seismic landfall rates of the crust caused by the Mw9.2 December 2004 Sumatra-Andaman Earthquake that also generated the devastating Indian Ocean tsunami. The exclusion of recent tidal data from the analysis does not change the shown rates as the length of post-earthquake tidal data is relatively much shorter than the one used in the analysis. In the long run, however, accurate rates of region-wide post-seismic downward motions will be ultimately important because the movements, as reported by studies on past big earthquakes, could last for decades. For a more comprehensive picture of what is happening in the sea, dual-crossover minimization analysis of multi-mission altimetry data covering the 1993-2009 period are undertaken. Altimetry results confirm that sea level rises in the Gulf of Thailand are not even. Average of near tide gauge rates provided by altimetry is 5.7 mm/yr in the north of the Gulf whereas a slower trend of 3.8 mm/yr is detected in the west. Higher rates are also detected in the open boundary with South China Sea. The remaining differences between the rates provided by satellite altimetry and GPS-corrected tidal data can be explained by interannual variations like ENSO and particularly decadal variations such as solar activity and lunar nutation that are not averaged out and still present in altmetry data. As climate-change induced sea level rises are being amplified by rapid post-seismic downfall of the land (currently estimated at around -10 mm/yr) more intense coastal erosion and frequent floods at coastal urban areas and river deltas throughout the region can be expected. There is an urgent need to re-evaluate the currently-accepted scenario of coastal-sea interaction and also a reconsideration of flood protection measures.

Sea-Level-Rise Trends Along the North Indian Ocean Coasts from Past Tide Gauge Records and Global Reconstruction Estimates

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Regional sea-level rise in the north Indian Ocean coasts was studied using past tide-gauge records. Among the many tide-gauge records that are present in the region, the one at Mumbai is more than 100 years old.

Inter-consistency checks among the tide gauge records in the north Indian Ocean was made for all the records longer than 20 years and it is shown that these records are consistent with each other and can be used for sea-level-rise trend estimates (Unnikrishnan and Shankar, 2007). We estimated the trends in mean-sea-level rise for selected records having duration of more than 40 years. After applying the GIA (Glacial Isostatic Adjustment) corrections, the trends varied between 1.06 mm/year to 1.75 mm/year, with an average value of 1.30 mm/year. However, the record at Diamond Harbour, shows a trend of about 5.74 mm/year. The tide gauge at Diamond Harbour is located in the Indo-Gangetic deltaic region, which is undergoing subsidence, as reported by Goodbred and Kuel (2000) based on sedimentological evidences. This suggests that the large trend of sea-level rise found at Diamond Harbour is likely to be associated partly due to subsidence of the delta.

The estimated sea-level rise trends are compared with global reconstruction estimates (Table 1) made by Church et al. (2004) for the period 1950 to 2000. The values of sea-level rise trends, except at Kolkata, from the global reconstruction estimates are close to 2 mm/year. As expected, spatial variations are not fully captured in the reconstruction estimates. However, the large trend found at Diamond Harbour (Kolkata) is found to match well with the reconstruction estimate.

Table 1. Sea-level-rise trends (Glacial Isostatic Adjustment corrections included) from past tide gauge records and global reconstruction estimates. (In: Unnikrishnan and Shankar, Global and Planetary Change, 2007).

Tide gauge station	Net sea-level-rise trend (mm yr^{-1}) from tide gauge data	Sea-level-rise trend from global reconstruction estimates (mm yr^{-1})
Aden	1.37	2.13
Karachi	1.06	1.94
Mumbai	1.20	2.06
Kochi	1.75	1.68
Vishakhapatnam	1.09	2.42
Diamond Harbour (Kolkata)	5.74	4.86

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Global Glacier Mass Balance: Modelling and Uncertainties

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More than 10^5 small glaciers and ice caps exist distributed over the entire globe ranging from small glaciers in the tropics to small ice sheets surrounding the Antarctic ice sheet. Their total volume is limited, but the fast mass turnover implies that volume changes of small glaciers have to be included in the discussion of sea level change on century time scales, which is illustrated by the notion that glaciers contributed about 45% to the observed eustatic sea level rise over the period. 1961-2003.

Moreover, we also know that sea level change observations vary considerably in space. Explanation or attribution of these observations require a careful consideration of processes leading to the spatial pattern, which among other processes naturally includes the contribution of small glaciers given their distributed nature. For that reason many attempts have been made to model the contribution of small glaciers to sea level for the past and next century. Limited data complicate this task as well as a large variability of climate parameters involved. To simulate past glacier fluctuations we can use glacier length fluctuations, but for future predictions we need to use volume area considerations to take areal changes into account, as not each individual model can be modelled. In order to deal with the spatial and temporal climate variability we need to rely on global climate models with good skills with respect to climatologically mean precipitation and temperature change. This is needed as the mass balance sensitivity depends strongly on the precipitation and volume changes are dominated by temperature changes.

In this presentation we will discuss the possibilities for modeling the mass balance of glaciers and indicate sources of uncertainties.

Local Sea Level Estimates Based on IPCC SRES Scenarios

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Sea level change is not spatially uniform and regional variations might be considerably larger than the few 0.1 mm/yr as suggested in the IPCC AR4 report. In the IPCC AR4 report, projections are presented for eustatic sea level change for the 21st century using SRES scenarios. Here, we present for the same scenarios local projections. The model ncludes a glacier model based on volume-area scaling considerations. For Greenland and Antarctica IPCC AR4 estimates are used, both for surface mass balance as the dynamical response. The ice mass changes are used in a self-gravitating se level model, which includes rotational changes as well. Thermal expansion is calculated at a regional scale based on the global circulation models used for AR4. Adding those to changes from the ice contribution yield regional patterns of sea level change. The results show the variability due to different scenarios as well as to different climate models. On average Islands in the Pacific show a sea level rise above the eustatic value and most coastal region in the Northern Hemisphere show values below the eustatic value. Implications are shown for key delta areas around the world.

Ice2sea Programme - Progress Report

David G. Vaughan[1] on behalf of the ice2sea participants

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Ice2sea is an EU Framework 7 funded project with 24 partners across Europe with the goal of constraining predictions of contributions of continental ice to sea-level rise over the next 200 years. We will do this through an integrated programme that includes targeted studies of key processes in mountain glacier systems and ice caps (e.g. Svalbard, Patagonia), and in ice sheets in both polar regions (Greenland and Antarctica); improved satellite determinations of changes in continental ice mass; development and implementation of ice-sheet/glacier models to generate detailed projections of the contribution of continental ice to sea-level rise over the next 200 years. We will deliver these results in forms accessible to scientists, policy-makers and the general public, which will include clear presentations of the sources of uncertainty. We are now a year into the project and in addition to some initial model output, recent field campaigns have provided data to be analysed. We summarise progress made to date, the targets for the coming year, and explain how you can stand informed and perhaps get involved in ice2sea.

Satellite-based Observations of Sea Level Rise from Large Ice Sheets

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The Greenland and Antarctic Ice Sheets are undergoing rapid changes. Recent observations point to an accelerating ice loss in both Greenland and Antarctica. These changes were not predicted by large-scale, shallow-ice approximation ice sheet models. Hence the role of observations remains essential to characterize the time and spatial evolution of these mass changes and to estimate the ice sheets contribution to sea level rise. Satellite observations in the past decade have transformed our knowledge of the contemporary contribution of the Antarctica and Greenland ice sheets to sea level rise. While significant advances have been made to estimate ice sheet mass balance using a variety of independent techniques, over different time periods, some disparity remains between the results.

Recent observations of acceleration in the ice mass loss help reconcile some of the differences between estimates. In addition when the estimates are compared in light of their limitations, the three major techniques of mass balance assessment (altimetry measurement of ice-sheet volume change, InSAR based mass budget method, and direct measure of changes in the ice sheet mass balance) agree on key aspects relevant to short term prediction of sea level rise, in particular on the rate of change of the mass loss with time.

Increasing Rates of Ice Mass Loss from the Greenland and Antarctic Ice Sheets Revealed by GRACE Gravity Satellite Measurements

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We use monthly measurements of time-variable gravity from the GRACE (Gravity Recovery and Climate Experiment) satellite gravity mission to determine the ice mass-loss for the Greenland and Antarctic Ice Sheets during the period between April 2002 and February 2009. We find that during this time period the mass loss of the ice sheets is not a constant, but accelerating with time, i.e., that the GRACE observations are better represented by a quadratic trend than by a linear one. Implying that the ice sheets contribution to sea level becomes larger with time. In Greenland, the mass loss increased from 137 Gt/yr in 2002-2003 to 286 Gt/yr in 2007-2009, i.e. an acceleration of -30 +/-11 Gt/yr^2 in 2002-2009. In Antarctica the mass loss increased from 104 Gt/yr in 2002-2006 to 246 Gt/yr in 2006-2009, i.e., an acceleration of -26 +/-14 Gt/yr^2 in 2002-2009. The observed acceleration in ice sheet mass loss helps reconcile GRACE ice mass estimates obtained for different time periods. Satellite observations can clearly show that the mass loss of the ice sheets is increasing with time and point out the spatial pattern in ice mass loss, identifying active sectors and new areas of change. The combined contribution of Greenland and Antarctica to global sea level rise is accelerating at a rate of 63 +/- 19 Gt/yr^2 during April 2002-February 2009, which correspond to an equivalent acceleration in the increase of sea level rise of 0.2+/-0.05 mm/yr^2 during this time. This large acceleration illustrates that the two ice sheets play an important role in the total contribution to sea level at present, and that contribution is continuously and rapidly growing. Continuous observations of ice mass-loss, such as those presented here, will be crucial for constraining present day ice sheet mass balance, their sea level contribution, and for gaining confidence in the results and provide robust observational constraints for future ice sheet models.

Understanding and Modelling Marine Outlet Glacier Dynamics

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Marine based outlet glaciers of polar ice sheets currently undergo rapid dynamic changes such as flow acceleration, thinning and terminus retreat and cause major concern regarding their contribution to future sea level. These dynamic changes were not included in the IPCC 2007 predictions for sea level rise due to the inability of the current generation of ice sheet models to reproduce such behaviour, as they are lacking the needed spatial resolution, model physics and understanding of the controlling processes and forcings. This study presents a first step in the development of numerical models with realistic behaviour of marine outlet glacier dynamics and investigates the recent rapid changes and the involved feedback mechanisms and controls.

We use a high resolution prognostic flowline model that includes basal, lateral and longitudinal stresses and a robust treatment of groundingline motion and apply it to three real world examples of rapidly changing tidewater outlet glaciers: Helheim Glacier and Jakobshavn Isbrae in Greenland and Crane Glacier a former tributary of the collapsed Larsen B ice shelf in the Antarctic Peninsula. We perform perturbation model experiments in order to investigate the sensitivity to changes in basal lubrication, ocean melt, backpressure from sikkusak/sea-ice and calving and compare the modelling results with observed changes.

We find that the recent dynamic changes can not be explained with enhanced basal lubrication from surface melt and that the flow acceleration and thinning originate from perturbations at the terminus, such as reduced buttressing, increased calving or enhanced ocean melt and that these changes propagate rapidly inland through dynamic coupling. The speed with which these changes propagate upstream is in the order of a few times the flow speed. In line with this, the modelling shows extremely rapid dynamic adjustment and high sensitivity of such marine outlet glaciers to perturbations at the marine boundary which provides an explanation for the almost synchronous behaviour of these glaciers to short-term fluctuations in climate or ocean conditions. This implies that the recent high rates of dynamic mass loss from Greenland are of transient nature and care should be taken when extrapolating to the future. We further find that the position of the calving terminus is a major control in the dynamics of such marine outlet glaciers and demonstrates the urgent need for a more realistic representation of the calving process in numerical models in order to improve our ability to predict the sea level contribution from marine outlet glacier acceleration.

Sea Level Studies at GKSS, Germany

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At the Institute of Coastal Research, GKSS Research Center, Germany, different aspects of sea level variations are studied, namely:

1) methodical issues of deriving *global* sea level changes from limited empirical evidence, and

2) present and possible future changes of *regional* sea level change in the North Sea and Baltic Sea

The estimation of **past and future global sea-level rise (GMSL)** is burdened a number of obstacles, among them the limited evidence of sea level change in the past and incomplete inclusion of processes in scenarios generated with process based models. Thus, statistical methods contribute significantly to our quantification of GMSL.

Estimations of GMSL variations are based on a limited number of long gauge records. One way to evaluate the uncertainty in these estimations is to compare the estimated GMSL with observations with global coverage, either from a dense network or from satellite data, in a recent period. We test such methods by employing the 'perfect model approach' by sub-sampling the output of a coupled model simulations mimicking the availability of observational records. Using the laboratory world of a millennial climate simulation, we find one such method to underestimate GMSL change in historical times, but to overestimate the increase in the 20th century.

Statistical models, such as (VR) $dH/dt = r_0 + a\,T + b\,dT/dt$, have been used to estimate possible **future changes of GMSL**. Here, H= global represents GMSL, T global mean temperature and t time. The physical mechanisms that justify the form of VR are not fully understood. The parameters r_0, a and b of VR are estimated from time series of reconstructions of GMSL from 1880-2000. These reconstructions are strongly smoothed, so that at most 8 independent samples are available.

Open problems related to VR are:

- The estimated value of *b* is negative, meaning that the third term would assign rising temperatures to declining sea-level rise

- The estimated value of *b* is very sensitive to the prior smoothing of the time series, turning from negative to positive roughly at the time scale of 30 years, the one used by VR.

- Would another form of the VR-model (e.g., replacing the temperature derivative by a weakly non-linear term) fit the observations as good as VR and yet project significantly different results for the long-term future?

While major efforts have been made in the last IPCC report to quantify past and potential future global mean changes, **regional changes of mean sea level (RSL)** has received only little attention. Since this is also the case, surprisingly, for both, the North Sea and Baltic Sea, efforts have been initiated to determine and to quantify RMSL changes for both regions.

For the **North Sea** an Empirical Orthogonal Function (EOF) analyses from 15 major tide gauges in German Bight, in the south western part of the North Sea, has been performed. The analysis reveals that the leading mode represents a coherent signal among all tide gauges that accounts for more than 90% of the observed variance. While the residuals account for only a small fraction of the observed variance and are not coherent between the different tide gauges we propose that the leading EOF may provide an estimate of observed relative RMSL changes in the German Bight while the residuals provide local changes at the tide gauges due to other reasons such as local water works, relocation of tide gauges etc. From the time coefficient series of the leading EOF mode a relatively constant rate of about 1.74 mm/year over the period 1924-2008 is inferred. Trends computed over consecutive 20-year periods indicate that rates of RMSL increase were relatively high during the past few decades but not higher than at earlier times.

The **Baltic Sea** is a semi-enclosed nearly tideless sea, which is connected to the Atlantic through the North Sea to narrow and shallow sounds.

Its RMSL is affected by a number of processes, which are insignificant in the North Sea, namely a mean surface salinity gradient from about 20 to 5 psu from NE to SW and a isostatic rebound from the last deglacation, with the Earth crust in the Northern Baltic rising at ~10mm/year and sinking in the South by ~1mm/year. Decadal sea-level variations in the northern and eastern Baltic Sea are strongly influenced by the atmospheric circulation, whereas RMSL variations in the Southern Baltic are better described by area-averaged precipitation through salinity changes and thus to changes in water density. The long term linear trend in sea level is thought to reflect isostatic changes. Scenarios of possible future air pressure changes point to future trends in sea-rise of the central and eastern Baltic Sea of the order of 1 to 2mm/year – additional to the isostatic change and the regional manifestation of GMSL. Using precipitation as predictor for the Southern Baltic Coast, the same scenarios cause significant future trends of about 0.4 mm/year.

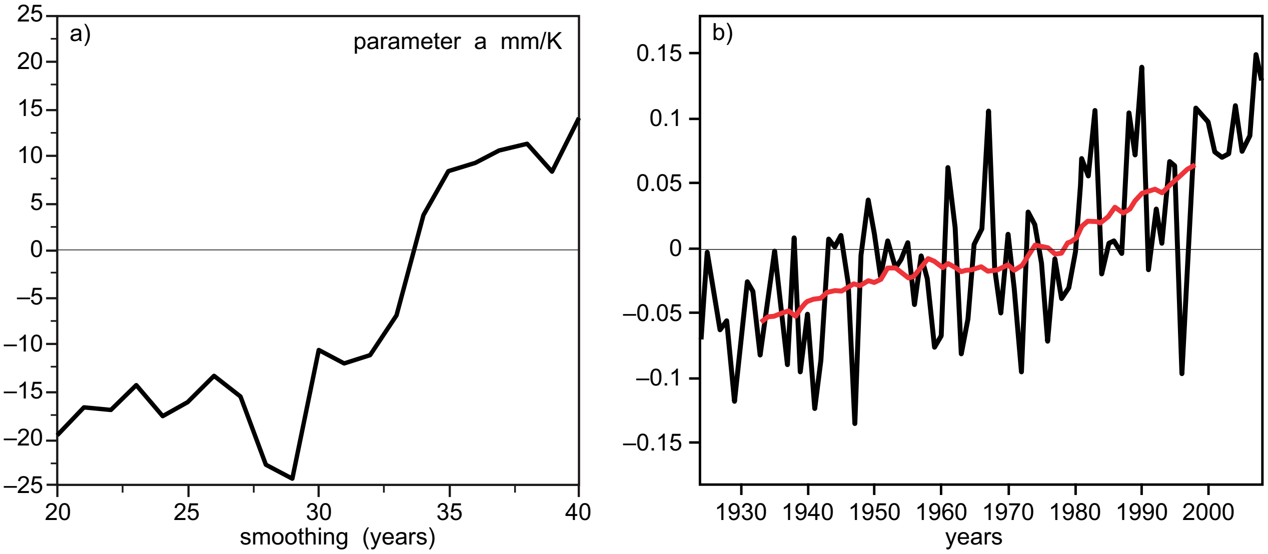

Figure 1. a) Dependency of the estimated values of the parameter in the VR-model as a function of prior smoothing of the global temperature and global mean sea-level data; b) Estimated regional mean sea level (time series of the leading EOF mode of annual mean RMSL) in the German Bight, North Sea – in red: the 19-year moving average. Units: m

Observed Linear Trends in Halosteric and Thermosteric Sea Level Rise over the Past 50 Years

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A new global analysis of linear trends in historical and Argo Program ocean profile data (Durack and Wijffels, 2010) quantifies both the thermosteric and halosteric changes in sea level down to 1800m over the past 50 years, and their regional patterns. Total steric change since 1950 is 35mm (27 mm) integrated to a depth of 1800m (700m). Of this 6mm or 20% (3mm or 10%) is due to halosteric effects. Regional patterns of steric change show highs along the axis of the Antarctic Circumpolar Current (likely associated with its southward shift) and in the North Pacific and Atlantic subtropical gyres. Reduced steric sea level is found around northern Australia, the eastern Indian Ocean and the subpolar Northwestern Pacific. Halosteric effects are significant everywhere, with contraction (enhanced salinity) throughout the Atlantic between 45N and 45S, the North Indian Ocean and expansion (freshening) through most of the Pacific and Southern Oceans. The pattern of halosteric change largely reflects a strengthening of interbasin salinity contrasts (both surface and subsurface) likely due to an enhanced hydrological cycle.

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Sea-Level Rise Observations in Singapore

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Singapore recently completed a study on climate change impacts on the coasts. The report has not been made public except for some results announced in the Parliament (Straits Times, 9.3.2010). By 2100 the report projected a temperature increase between 2.7°C and 4.4°C from the present average of 26.8°C and no discernible trend in rainfall pattern. The sea-level rise would be between 24 and 65 cm.

It was acknowledged in Parliament that the study was not the last word on the climate change debate. There is a need to improve the knowledge as more information and data become available and climate change models become more robust (Straits Times, 9.3.2010). More studies are required to examine the sea-level rise threat (Sunday Times, 14.3.2010).

The tide records in Singapore are too short to show any long-term sea-level rise or fall. During a year a number of high spring tides occur at about 3.2-3.3 m. When coupled with a storm surge another 0.2-0.6 m can be added to these heights. The highest recorded spring tide was 3.9 m in February 1974 leading to widespread coastal erosion and flooding of the coastal parks (Wong 1992). In December 1999 another spring high tide at 3.4 m also led to increased beach erosion and coastal flooding.

The 3.4-3.9 m zone indicated by these two highest recorded tides could be regarded as the inundation range for Singapore when high spring tides occur with a storm surge which seems to increase with the shift of the typhoon tracks nearer to the equator (Figure 1). Singapore was affected by Typhoon Sarah (1956), Tropical storm Greg (1996) and Typhoon Vamei (2001).

Since early 1990s the platform level for reclaimed land in Singapore has been raised to 1.25 m above the highest tidal level (3.9 m in February 1974). Drainage has been improved considerably to reduce the area of flooding including measures to expand the network of sensors and to redesign drainage systems. However, for a projected sea-level rise of 1 m the new design height in Singapore is slightly higher than the inundation zone (Figure 1). Given the fact that studies after the IPCC Fourth Assessment Report are projecting a multi-metre sea-level rise Singapore needs to re-examine its vulnerability to a sea-level rise.

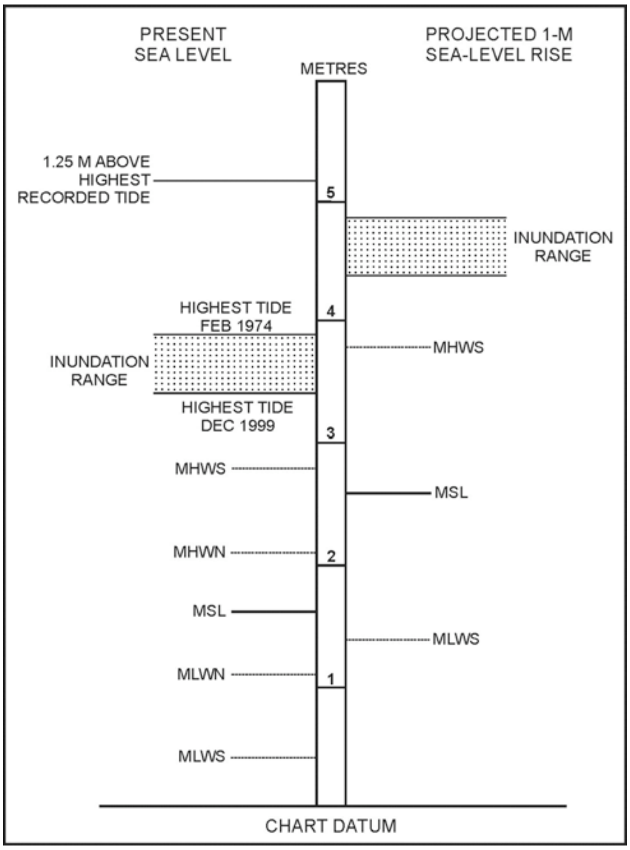

Figure 1. Inundation zone of present sea level and projected 1-m sea-level rise

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Studies of 19th and 20th Century Trends and Accelerations in Mean and Extreme Sea Levels

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Important questions in studies of global sea level change are whether the sea level rise experienced at most locations during the 20th-21st centuries is a continuation, or acceleration, of the trends of the 19th century and earlier. This topic is usually addressed by inspection of the small number of available long sea level records, mostly from Europe and North America; with the use of 'data archaeology' of short periods of historic sea level measurements from various locations during the 18th and 19th centuries (including interestingly from several sites in the southern hemisphere); and by means of archaeological and geological techniques. Of the latter, the use of data from salt marshes is being exploited by several groups and offers the possibility to provide sea level records several centuries long. These salt marsh records can be compared to those from tide gauges nearby, where they exist, during their periods of overlap, or can be used to extend the spatial coverage of tide gauge information.

We shall explore some of these issues in this poster. Time series for two centuries or more from the longest European records will be presented. These show evidence for a slow positive acceleration in sea level between the 19th and 20th centuries. Then, using the more copious data sets from the late 19th century onwards, the evidence for accelerations in regional and global-average sea level on timescales of several decades and longer will be reviewed. Many data sets display evidence for a positive acceleration, or 'inflexion', around 1920-1930 and a negative one around 1960, with higher rates restored since the 1990s. These inflexions of course contribute to the long term 19th -20th century acceleration. However, these decadal characteristic features are not always found in records from other parts of the world. Although some aspects of the sea level time series are consistent with changes in rates of globally averaged temperature changes, volcanic eruptions and natural climate variability, modelling undertaken so far has been unable to describe these features adequately. This emphasizes the need for a major enhancement of the sea level data set, especially for those parts of the world without long tide gauge records, in order to obtain greater insight into the spatial dependence of accelerations. Therefore, a number of complementary methods must be employed, of which salt marsh techniques offer the possibility of obtaining time series similar to those that would have been obtained from coastal tide gauges.

An additional question in studies of trends and accelerations is whether changes in extreme sea levels have been similar to those of mean levels. Extremes are more difficult to study than means for various reasons (including difficulties of access to data) and investigations tend to be limited to the last few decades if one is to have reasonable regional or global coverage of information. We have recently made use of a quasi-global tide gauge dataset to investigate extreme sea level events and their spatial and temporal variability. Modern methods based on a non-stationary extreme value analysis were applied to the maxima of the total elevations and surges for the period 1970 onwards, while a small subset of the data was used to study changes over the 20th century. The analyses demonstrate the magnitude and timing of the seasonal cycle of extreme sea level occurrence, the magnitude of long-term trends in extreme sea levels, the evidence for perigean and nodal astronomical tidal components in the extremes, and the relationship of the interannual variability in high water levels to other ocean and atmosphere variations as represented by climate indices. The subtraction from the extreme sea levels of the corresponding annual median sea level was found to result in a reduction in the magnitude of trends at most stations, leading to the conclusion that much of the change in extremes is due to change in the mean values. This is clearly an important conclusion for coastal planners, if that conclusion applies also to the future, as predictions of mean sea level change are difficult and uncertain enough without additional uncertainties being introduced with regard to projected extremes. The poster will summarise results from some of this work.

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Surface Mass Balance Observed from Coastal to Hinterland of East Antarctic Ice Sheet in Recent Decades

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The net snow accumulation rate along the Chinese national Antarctica Research Expedition (CHINARE) route during 1997-2008 was measured by stake and stake arrays. There is a slow decrease pattern from Zhongshan to Dome A, consistent with that in the other regions like Terra Nova Bay to Dome C (Frezzotti et al., 2005, 2007) and Syova Station to Dome Fuji (Furukawa et al., 1996). In general, the accumulation rate is high near coast and decreases toward the inland till ~202 km to coast, then increases till ~350 km, then decreases again till ~524 km. The accumulation rate during 524-800 km is stable and low. The ice divide area from 800 to 1128km also has a slightly increase trend when get closer to the dome, whereas is the lowest area of accumulation.

Along CHINARE traverse line, the steeply sloping section (68-202 km) has an average accumulation rate of 157.2 kg m^{-2} yr^{-1} during 2005-2008 and 426.7 kg m^{-2} yr^{-1} during 1997-1999. The slow-upward section from 202 km to 524 km is characterized by an average accumulation rate of 72.6 kg m^{-2} yr^{-1} during 1999 to 2008, The wind direction of the flattest area (524-800 km) is concentrative, inducing many hard snow crusts here, and there is an average accumulation rate of 52.3 kg m^{-2} yr^{-1} during 1999 to 2008. The average accumulation rate (71.8 kg m^{-2} yr^{-1}) of the ice divide area (800-1128 km) is higher than the flattest area though it is farther from coast. The Dome area (1128-1246 km) has the lowest annual average accumulation rate of 34.7 kg m^{-2} yr^{-1} during 2005-2008. Stake array increases the representativeness of for snow accumulation rate compared with single stake. For single stake, it is confirmed that data of the 3-year running mean can be representative of the precipitation minus evaporation, while 1-year accumulation data only reflects precipitation plus the local noise.

Ten firn cores at the coastal regions of east Antarctic ice sheet were contrasted for their records of snow accumulation for the last 5 decades in the 20th century. It shows that snow accumulation at the five sites over the eastern area (i.e., GC30, GD03, GD15, DT001 and DT085, which locate at Wilks Land and Princess Elizabeth Land) increased, whereas these at the western area (i.e., Core E, DML05, W200, LGB16 and MGA, which locate at Dronning Maud Land, Mizuho Plateau and Kamp Land) decreased. The increasing rate over the eastern coast was between 0.34~2.36 kg m^{-2} a^{-1}, and the decreasing rate over the western coast between -0.01~-2.36 kg m^{-2} a^{-1}.

Clearly, preciser assessment the surface mass balance of the east Antarctic require separate calculation of in-situ data collected from coastal, inland and hinterland of the ice sheet.

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Interdecadal Variability and Rising Trend of Sea Level Along the Japanese Coast

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Sea level rise due to the global warming is one of the most crucial issues in the island countries. Global mean sea level has risen at 1.2-2.2 mm/year for the 20th century and has been accelerated in the last two decades (IPCC, 2007). However, since long-term sea level trend varies according to the different regions, it is important to understand regional sea level variability and underlying mechanisms.

Japan is located at the latitude of boundary between the subtropical and subpolar gyres in the North Pacific and the area where the strong Kuroshio and the Oyashio currents meet. Therefore, sea level along the Japanese coast is greatly influenced by the change in these current systems.

Historical tide gauge data show that sea level along the Japanese coast has no significant trend during the 20th century (Figure 1). Rather, bidecadal variability and simultaneous variation along the Japanese coast are remarkable (Senjyu et al., 1999; Yasuda and Sakurai, 2006). In order to examine the causes of this sea level variability, ocean general circulation model (OGCM) experiments forced by the historical atmospheric reanalysis data have been conducted (Yasuda and Sakurai, 2006). The long-term variability of the sea level along the Japanese coast is mainly due to the baroclinic Rossby waves forced by changes in the large-scale wind stress fields in the North Pacific with a lag of several years. The bidecadal variability is caused primarily by the meridional shift of the boundary between the subtropical and subpolar gyres, which is forced by the shifting of the westerlies over the central North Pacific. In addition, decadal variability with a north-south dipole structure along the Japanese coast has been observed in the late 20th century. This variability results from a change in the strength of the subtropical gyre due to a change in the magnitude of the westerlies. Furthermore, the rising (descending) trend of the sea level observed in the southern (northern) part of Japan in the past 50 years is determined by the increasing trend of the midlatitude westerlies. In the 1990s, sea level along the Japanese coast has risen (Figure 1). Although this is partly explained by the dynamical response to the wind stress fields, it can be considered that the global mean thermal expansion contributes considerably.

On the sea level rise along the Japanese coast in the future climate, its spatial pattern along the Japanese coast is important in addition to the influence of the global mean sea level rise. Some of IPCC-AR4 models tend to project the sea level rise for the 21st century larger in the northern part of Japan than that in the southern part, or vice versa (e.g., Sakamoto et al., 2005; Sato et al, 2006). These differences are due to the different projections of magnitude and position of the Kuroshio and Oyashio currents, which depend on the future changes in the Aleutian Low and related midlatitude

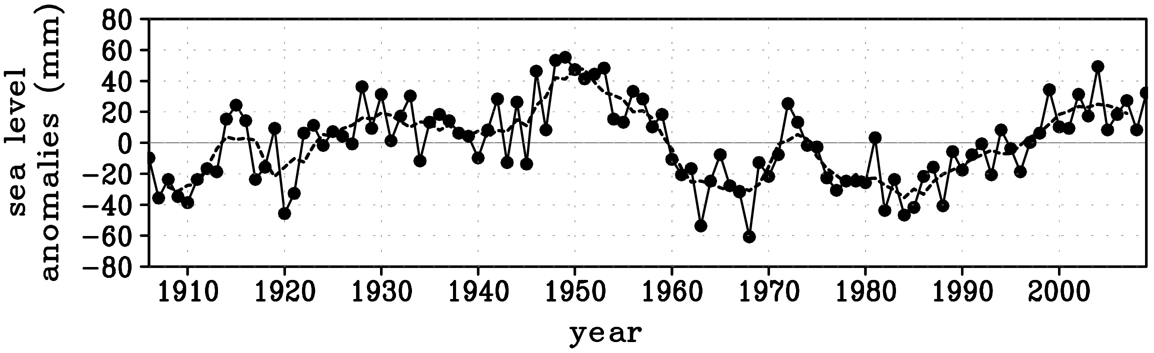

Figure 1. Time series of annual mean sea level anomalies averaged along the Japanese coast calculated from tide gauge data. Dashed line denotes 5-year running mean values.

westerlies. Therefore, in order to have a reliable projection of the sea level rise along the Japanese coast, it is necessary to reduce uncertainties on the atmospheric changes in the midlatitude North Pacific associated with global warming.

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Detecting Holocene Sea Level Signals in Antarctica

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Mid to Late Holocene sea-level change can be used for evaluating long-term stability of the Antarctic ice sheet since the end of the last major, approximately 8,000 years ago. Ongoing global warming may trigger disintegration of this ice sheet, with collapse of the West Antarctic Ice Sheet alone potentially producing a more than 3 to 4 m global sea-level rise. Relative sea level records from sites far away from former ice sheet regions (far-field) provide information on total volume of the ocean mass change, which can be interpreted as global ice volume change. However, understanding mechanisms for the ongoing ice sheet fluctuations requires information on the source of meltwaters, provided by records near the Antarctic ice sheet. To address the paucity of information from this region, we have employed two new methods to understand melting history of Antarctic ice sheets, namely cosmogenic radionuclides (CRN) and compound specific isotopes (CSI) measurements, both of which w ill provide a more complete history of ice sheet behavior. Cosmic rays began bombarding the surface of rocks in Antarctica after deglaciation. Hence, the amount of CRN is proportional to minimum exposure age after ice sheet ablation. CSI is useful for analysis of sediments proximal to ice sheets due to the differing isotopic signals between ice and seawater, up to ca. 300 per mil for hydrogen isotopes. Therefore, meltwater signals can be recorded in CSI produced from surface dwelling algae. Another major obstacle for Antarctic marine geological study is the difficulty in applying radiocarbon dating for to two basic reasons; lack of foraminifers and anomalously old TOC ages because of old carbon contamination from the Antarctic continent. We are using compound specific radiocarbon dating to solve this problem. In this presentation, we introduce these two measures to reconstruct the melting history of Antarctic ice sheet during the Holocene using two particular examples from Lutzow Holm bay in East Antarctica and Ross Sea of West Antarctica.

The Contribution of Glaciers and Ice Caps to Global Sea Level Rise: State of Knowledge, Challenges and the Way Forward

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The 4th Assessment Report of the Intergovernmental Panel on Climate Change (Lemke et al., 2007) estimates the global area covered by glaciers and ice caps between 510,000 and 540,000 km^2; excluding the glaciers and ice caps surrounding the two ice sheets in Greenland and Antarctica. Estimates for the corresponding total ice volume range from 50,000 to 130,000 km^3 which corresponds to a potential sea level rise between 15 and 37 mm. Based on regional averages of glacier mass balance measurements multiplied with estimates of corresponding glacierized areas, the contribution of glaciers and ice caps is estimated to be 0.37 mm a^{-1} in sea level equivalent between 1961 and 1990 and 0.77 mm a^{-1} between 1991 and 2004 (Kaser et al., 2006). Based on the same approach, recent mass balance measurements indicate an annual contribution of around 1 mm a^{-1} since the turn of the century (Meier et al., 2007; WGMS, 2009). These studies are largely based on the glacier inventories and mass balance series compiled and disseminated by the World Glacier Monitoring Service (WGMS; www.wgms.ch) through the Global Terrestrial Network for Glaciers (GTN-G; www.gtn-g.org). Corresponding overviews are given in WGMS (2008), Zemp et al. (2009), and in the abstract/poster by Zemp et al. (2010, this workshop).

The present estimates of glacier contribution to sea level rise are hampered by the fact that: (a) no complete detailed inventory of the Earth's glaciers exists; (b) the estimation of the overall ice volume of glaciers contains large uncertainties; (c) the spatial distribution of the available mass-balance series is disproportionate to the global ice cover; and (d) the small sample of mass-balance observations is (most probably) not representative for the entire sample of glaciers (Zemp et al., 2009).

Most of the approaches use the regional ice extents of Dyurgerov and Meier (2005 and earlier versions; mainly based on WGMS, 1989) as a baseline inventory to calculate the overall potential sea-level rise equivalent as well as sea level changes. A detailed inventory, including information on glacier location, size and altitude extent, is yet only available for about 100,000 glaciers covering about 240,000km^2. This corresponds to only 62% of the approximate total number and 30% of the overall glacier area based on rough estimates from Meier and Bahr (1996) and Dyurgerov and Meier (2005), respectively. As a further uncertainty factor, the existing inventory contains no information on the proportion of ice below sea level and ice temperatures. There are only a few glaciers where thickness measurements have been carried out (so far not compiled by the WGMS). Different approaches exist for estimating the overall ice volume (e.g., Haeberli and Hoelzle, 1995; Bahr and others, 1997, Farinotti et al., 2008), but they all contain a number of uncertainties that could amount to 30–50% of the total ice volume. The estimates of total glacier area and corresponding potential sea-level rise in Lemke et al. (2007), as correctly noted by the authors, do not include ice bodies around the ice sheets in Greenland (70,000 km^2 based on Weidick and Morrris, 1998) and Antarctica (169,000 km^2 based on Shumskiy, 1969) and, hence, might considerably underestimate the overall potential sea-level rise due to melting glaciers. As shown by Zemp et al. (2009), many of the regions with large ice covers, such as the Canadian Arctic, High Mountain Asia, South America and around the two ice sheets, are not represented by an adequate number of long-term mass-balance measurements. Mass-balance programs require intensive fieldwork and are usually carried out on glaciers that are easy accessible, safe and not too large. Hence, these glaciers are neither representative of the glacier size distribution nor of the elevation distribution of all glaciers, at least when compared with the presented data of about 100,000 glaciers with detailed inventory information (the data for an exact comparison are not available).

The current first-order estimates of the contribution from glaciers to past, present and future sea-level changes can only be improved significantly by completing a detailed baseline inventory of the Earth's glaciers as well as a review and enlargement of the available (measured) glacier thickness dataset. This would be needed to scale-up the few in situ series that we have to cover all glaciers. It is hoped that internationally coordinated efforts, such as the European Space Agency-funded GlobGlacier project (www.globglacier.ch), the Global Land Ice Measurements from Space initiative (www.glims.org), or the science program Ice2Sea by the European Union Framework-7 scheme (www.ice2sea.eu), will make major steps in that direction. Furthermore, it is necessary to continue and extend the present mass-balance network in respect of the global distribution of the ice cover and to make systematic use of remote sensing and geo-informatics to assess the representativeness of the available in situ annual mass balance series (Paul and Haeberli, 2008) and decadal ice volume changes of entire mountain ranges (e.g., Rignot and others, 2003; Larsen and others, 2007; Schiefer et al., 2007; Berthier et al., 2010).

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Annex 5: Scientific Projects and Programmes

The following list contains the scientific projects and programmes referred to in *Summary of the Discussions and Conclusions* and *Breakout Group Reports*, collected here as a resource for the reader.

ANDRILL	Antarctic Geological Drilling Research Project http://www.andrill.org/
ARGO	http://www.argo.ucsd.edu/
COMBINE	Comprehensive Modelling of the Earth System for Better Climate Prediction and Projection http://www.combine-project.eu/
CMIP	Coupled Model Intercomparison Project http://cmip-pcmdi.llnl.gov/
CRYOSat2	http://www.esa.int/esaMI/Cryosat/index.html
ERS2	European Remote Sensing Satellite 2 http://earth.esa.int/ers/
ESA	European Space Agency http://www.esa.int/esaCP/index.html
GLOSS	Global Sea Level Observing System http://www.gloss-sealevel.org/
GRACE	Gravity Recovery and Climate Experiment http://www.csr.utexas.edu/grace/
GRIMICE	Greenland Ice Sheet Model Intercomparison Experiment http://www.cesm.ucar.edu/events/ws.2009/Presentations/Tarn/LandIce/bamber.pdf
Ice2Sea	http://www.ice2sea.eu/
IceBridge	http://www.espo.nasa.gov/oib/
ICESat	http://icesat.gsfc.nasa.gov/
IMAGES	International Marine Past Global Change Study http://www.images-pages.org/
InSAR	Interferometric Synthetic Aperture Radar http://solidearth.jpl.nasa.gov/insar/
IODP	Integrated Ocean Drilling Program http://www.iodp.org/
ITASE	International Trans Antarctic Scientific Expedition http://www2.umaine.edu/USITASE/
NASA	National Aeronautics and Space Administration http://www.nasa.gov/
PAGES	Past Global Changes research project http://www.pages-igbp.org/
PALSEA	PALeo-Constraints on SEA Level Rise Working Group http://eis.bris.ac.uk/~glyms/working_group.html
SeaRISE	Sea-Level Response to Ice Sheet Evolution http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment
WCRP	World Climate Research Programme http://www.wcrp-climate.org/