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Confidence and sensitivity of sea-level reconstructions

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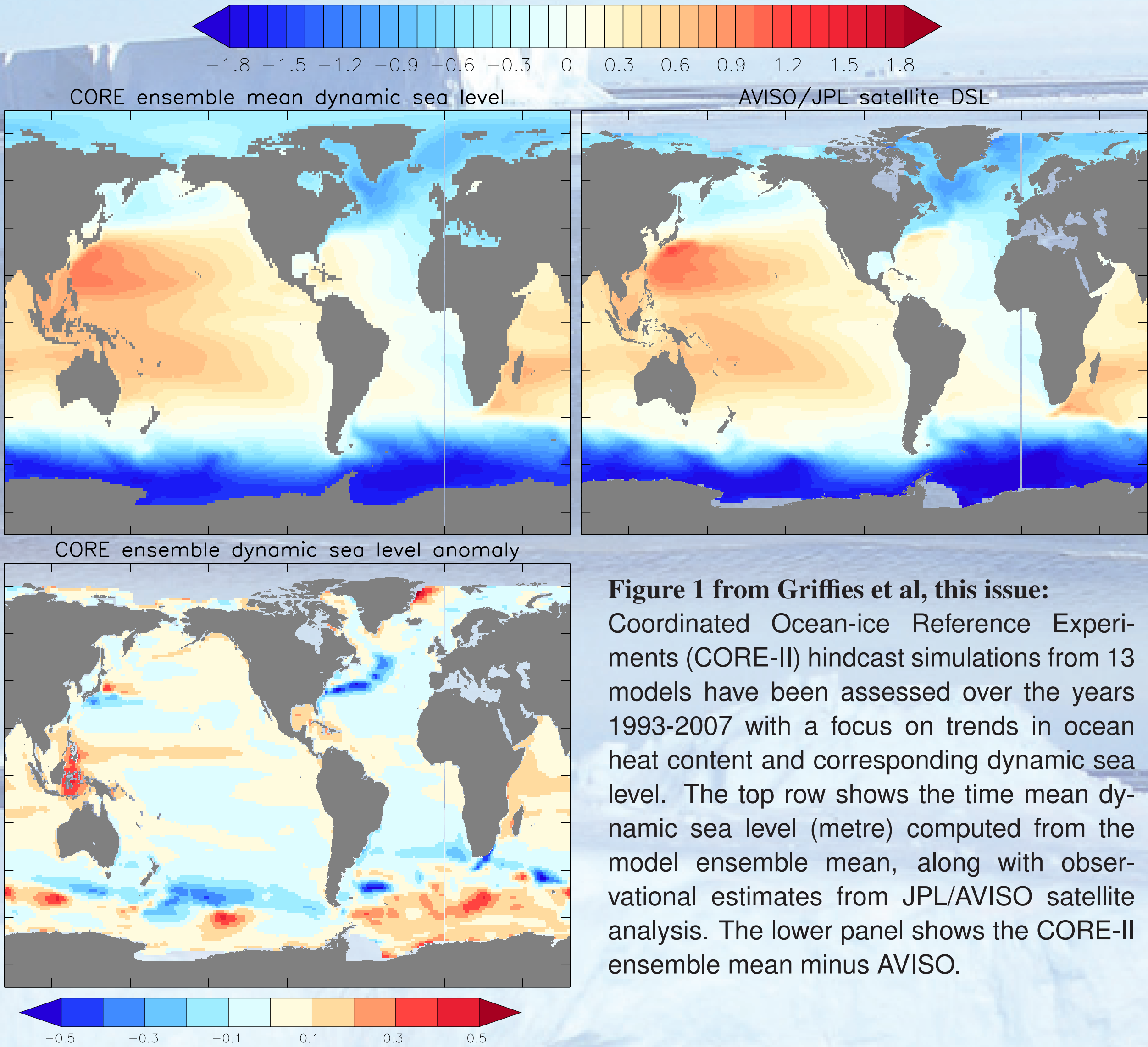

Figure 1 from Griffies et al, this issue: Coordinated Ocean-ice Reference Experiments (CORE-II) hindcast simulations from 13 models have been assessed over the years 1993-2007 with a focus on trends in ocean heat content and corresponding dynamic sea level. The top row shows the time mean dynamic sea level (metre) computed from the model ensemble mean, along with observational estimates from JPL/AVISO satellite analysis. The lower panel shows the CORE-II ensemble mean minus AVISO.

Cover images courtesy of S. Marsland

CLIVAR is an international research programme dealing with climate variability and predictability on time-sales from months to centuries. CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization,the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

WGOMD/SOP Workshop on Sea Level Rise, Ocean/Ice Shelf Interactions and Ice Sheets
Hobart, Australia, 18-20 February 2013

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The CLIVAR Working Group on Ocean Model Development (WGOMD) and CLIVAR/CliC/SCAR Southern Ocean Region Implementation Panel (SOP) convened a Workshop on Sea Level Rise, Ocean/Ice Shelf Interactions and Ice Sheets at CSIRO Marine and Atmospheric Research in Hobart, Australia, on 18-20 February 2013. The workshop brought together leading international scientists and early-career researchers from the ocean, ice-sheet, ice-shelf, and sea-level rise modelling and observational communities to explore the state-of-science and emerging pathways for development of the next generation of coupled climate models. More than one hundred scientists from 16 countries participated. 15 early career scientists (ECSs) were awarded funding to attend the meeting based on merit of their contributions (poster and oral presentations). The oral agenda was carefully prepared balancing plenary, overview talks with shorter talks by ECSs on key state of the art findings (11 talks out of the total 23 were given by ECSs).

Sea-level rise and the related potential coastal impacts are a topic currently drawing intense scientific and societal interest. The contribution from the instability of ice-sheet mass exchanges with the oceans remains a key uncertainty in our understanding of global sea-level rise. Predicting regional sea-level changes is further complicated by our limited understanding of how both natural variability of climate modes, along with climate change forcings, will impact the regional signature of sea-level rise associated with the mass redistribution of both the changing ocean and ice sheets. With these challenges in mind, the workshop had three aims: to assess the state-of-science of high-latitude land-ice interactions with the ocean; to identify priorities for reducing uncertainties in projections of global and regional sea-level rise; and to investigate pathways for the development of a new generation of climate models that incorporate interactive ice-sheet components.

Scene-setting pedagogical presentations provided context on the theory and observations of sea-level and land-ice science. Some of the noteworthy advances in reducing uncertainties presented at the workshop included reduced uncertainties related to Glacial Isostatic Adjustment (GIA), and improvements in the closure of the 20th century global mean sea-level budget as a sum of its components. A notable ongoing advance in ice-sheet modelling is the continuing development of two community modelling systems, the LANL Community Ice Sheet Model (CISM; http://oceans11.lanl.gov/trac/CISM) and the NASA/JPL Ice Sheet System Model (ISSM; https://issm.jpl.nasa.gov). Understanding the interaction between the ice sheets and the ocean also requires knowledge of the circulation and melt/freeze cycling in sub-ice shelf cavities. For the Southern Hemisphere, fully circumpolar ocean/ice-shelf models are beginning to emerge, although work remains to incorporate these efforts into coupled climate models. Such efforts will help to address uncertainties about the processes governing the oceans role in sub-ice shelf melting and freezing, for example the role of Antarctic coastal polynyas in moderating ice-shelf melting through coastal shelf mixing processes.

Ocean modelling, especially as a part of coupled climate modelling, is a fundamental component of the projection of future sea-level rise. This is particularly true for the regional patterns of sea-level variability and change. The ocean modelling community faces significant outstanding challenges regarding projection of future sea-level. Problems of ocean model bias and drift have not to date been sufficiently addressed, despite the importance of this for interpreting the wealth of model outputs now available through CMIP5. The WGOMD, through its ongoing role in promoting Coordinated Ocean-Ice Reference Experiments, is in a unique position to help identify and address the deficiencies of ocean models relevant to our understanding of global and regional sea-level projections. As such, the identification of the strengths and weaknesses of ocean models with respect to sea level change was also a key aim of the workshop. Updates on that work can be found in the Griffies et al. article contained herein. Some work has been done on both the steric and barystatic effects on sea-level rise by forcing ocean and coupled models with idealised ice sheet meltwaters, however the ideal of fully interactive coupled models incorporating dynamic ice-sheet components remains a work-in-progress.

In the future there remains a need for continued focus on both observational and modelling efforts in order to improve our understanding of the interactions between oceans, ice shelves, and ice sheets. The regional patterns of sea-level change will evolve as a superposition of forcings from both natural modes of variability and climate change. Better representation of climatic processes in models will remain fundamental to progressing the science, as will improvements in the way that we evaluate the plethora of information that models make available.

This special issue of CLIVAR Exchanges is devoted to presenting a selection of the science contributed by both speakers and poster presenters at the workshop. In addition to the Hobart workshop, panel meetings of WGOMD and SOP, including a joint session, were held. Reports from those sessions can also be found within this issue. It can be noted that the workshop topic is strongly aligned with some of the future activities of CLIVAR under the proposed framework of "Research Opportunities": in particular the "Dynamics of Regional Sea Level Variability" and "Ocean Heat Storage" research opportunities. Likewise, the science presented is strongly aligned with future work under the World Climate Research Program "Grand Challenges": particularly the "Cryosphere in a Changing Climate" and "Sea-Level Rise and Regional Impacts" Grand Challenges.

Further information about the workshop, including a selection of speaker presentations and poster abstracts, is available at http://www.clivar.org/organization/wgomd/sealevel.

Acknowledgements

This workshop was one in a series of Cutting Edge Science Symposia made possible through seed-funding granted by the CSIRO Office of the Chief Executive Science Team. We are grateful for sponsorship from the following organizations: Climate Variability and Predictability Project (CLIVAR); Commonwealth Scientific and Industrial Research Organisation (CSIRO); Climate and Cryosphere Project (CliC); World Climate Research Programme (WCRP); Intergovernmental Oceanographic Commission (IOC); US National Aeronautics and Space Administration (NASA); US Department of Energy (DoE); US CLIVAR; Antarctic Climate and Ecosystems Cooperative Research Center (ACE CRC); and the Australian Research Council Centre of Excellence for Climate System Science. We thank the scientific and local organising committees, the oral and poster presenters, and the workshop participants, for their contributions to the success of the workshop.

Dynamics of Sea-Level Rise

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Background

Changes in regional sea level are aspects of anthropogenic climate change that have far-reaching consequences for the security of much of the global population. Because regional sea level changes have to be considered as a superposition of global mean sea level and regional - some times even local - aspects of sea level, we need to understand all those aspects and underlying causes before we can provide projections of sea level change and assess their detailed societal implications. Available tide gauge measurements indicate that the globally averaged sea level has risen at a mean rate of 1.7–1.8 mm/year during the twentieth century (Jevrejeva et al. 2008, Church & White 2011) with a nominal uncertainty of ±0.3 mm/year; but because these values do not reflect uneven spatial sampling in time the uncertainty might be larger than specified. More accurate estimates of sea level rise are only available after satellite altimetry became available in 1993. These results suggest that global mean sea level rise during the past two decades has increased at a rate of ~3.2 ±0.4 mm/year (e.g., Mitchum et al. 2010, Nerem et al. 2010) which is faster than the twentieth-century average (e.g., Merrifield et al. 2009).

Since the IPCC Fourth Assessment Report (AR4, 2007) the scientific community has reached the position of being able to quantitatively close (to first order) the net global mean sea level budget during the second half of the twentieth century, taking into account contributions from all major contributing components (Cazenave et al. 2009, Cazenave & Llovel 2010, Church et al. 2011). Results show that historically an increased ocean heat content contributed significantly to the observed increase in global mean sea level (e.g., Bindoff et al. 2007, Domingues et al. 2008). However, new satellite observations indicate that the recently observed increased rate of sea level rise is caused only to about 1/3 by ocean thermal expansion, but about 2/3 by mass loss of glaciers and ice sheets (e.g., Bindoff et al. 2007, Church et al. 2011), indicating that contributions to global mean sea level from glaciers and ice sheets have become significant (e.g., Steffen et al. 2010, Rignot et al. 2011, Jacob et al. 2012). Observations suggest further that during the most recent years the contribution of ice masses originating from Greenland and Antarctica to sea level rise has increased (Rignot et al., 2011). Albeit still uncertain (Faezeh et al., 2013) the continuing monotonic increase in global mean sea level might suggest that thermosteric contributions to global means sea level might have declined further during recent years when a hiatus in global surface temperature was observed.

Because regional sea level change is the most relevant information for societal impact assessments of sea level change, it is urgent to investigate sea level variations and change on regional and local scale, including shelf seas and coastal areas, underlying dynamics and especially also interactions of the ocean circulation with the land-ice. In general terms, changes in regional sea level arise from a global mean increase superimposed by many dynamical and static contributions that result from changes in the ocean circulation, the terrestrial hydrosphere, the cryosphere, and the solid Earth, making this a unique and integral diagnostic of climate change (Milne et al. 2009, Church et al. 2010; Stammer et al., 2013). We also note that a significant fraction of contemporary local sea level changes are not related to contemporary climate change; instead to a large extent they reflect natural climate modes of variability, regional dynamics and on the local scale even non-climate-related anthropogenic changes.

Understanding contemporary regional sea level changes in terms of underlying physical and dynamical processes is essential for providing science-based information about the regional sea level change. Even for contemporary regional dynamical sea level changes we do not know in detail their forcing functions nor are we in a position where we can separate natural from anthropogenic changes. Moreover, substantial uncertainties remain in sea level reconstructions for the past few decades. To improve existing estimates, a continuing improvement to observations and analysis from tide-gauge and proxy sources is necessary.

Climate model simulations of future regional sea-level changes due to anthropogenic climate change on multi-decadal timescales show geographical variability, which is substantial compared with the global-mean sea-level rise. The pattern of such future projections can mostly be explained by local temperature and salinity changes, i.e., they are steric in nature, but are likely to be caused by a combination of changes in surface heat and freshwater forcing, changes in redistribution by interior mixing, and trends in the wind-driven and thermohaline circulation. Future circulation changes may alter fundamentally the ocean-land ice interaction on regional and local scale.

Initial studies on regional sea level projections were based on CMIP3 results (e.g., Slangen et al., 2011) and more recently on CMIP5 model output (Slangen et al., 2013; Carsen et al., 2013). Results provided insight into the intricate nature of regional sea level rise and indicated that especially for high-end end scenarios a significant fraction or regional sea level changes will be caused by changes resulting from ice sheet mass loss and associated responses of the solid earth.

Existing climate models largely disagree about patterns and magnitudes of sea level variability and change on regional scales arising from changes in the ocean, and it is entirely unclear whether they have sufficient skill in projecting regional sea level. To further improve our understanding of future regional sea level changes requires a much improved understanding of detailed dynamic processes involved today and in the future in circulation changes and of all processes involved in net changes in sea level on regional and local scale than what can be inferred from coarse resolution climate models. Accurate predictions of regional sea level change on decadal to centennial time scales are also required for impact, adaptation and vulnerability assessments for the coastal communities.

Main challenges

Understanding all relevant processes leading to sea level changes at any location of the ocean is a very challenging task because of complex underlying dynamics covering a broad range of temporal and spatial scales and requires an interdisciplinary approach involving expertise about the ocean, the cryosphere, the terrestrial hydrology as well as geodesy and geophysics on the one hand and social scientist on the other hand.

Climate projections suggest that global mean sea level is likely to continue to rise at an even increasing rate (e.g. Church et al., 2011) and it is likely that the contribution from ice sheets and glaciers will continue to increase during the next century. Beyond the 21st century, however, with sustained warming, the contribution from glaciers will level off because there will be little remaining glacier ice. However, the contribution from the Antarctic ice sheet is particularly uncertain and could become large; it depends on its dynamical response to the thinning and removal of ice shelves in a warming climate.

To foster progress in our understanding of past and present sea level changes and to obtain an understanding of uncertainties intrinsic to existing sea level projections, several challenges need to be addressed in the near future. Those can be grouped around the following topics:

I) Past and present Sea Level Changes and Processes

Evidence emerges that much of the observed regional sea level changes are dynamic in nature, reflecting natural climate modes superimposed to a global mean sea level change. With respect to these dynamical changes we have to understand in detail their forcing function (wind vs. buoyancy forcing) as well as what causes the forcing to change (natural/anthropogenic). Ocean modeling is of little use at present to decipher the response of the ocean to specific surface forcing functions and thereby to help improving the reconstruction of past sea level changes due to spurious model drift which to remedy requires novel forcing strategies.

Further progress requires

- A dedicated program to enhance our knowledge from past observations; possibly expand the proxy-data base and expand the use of models for studies of past sea level.
- We need observations of deep ocean tempertature and salinity changes and we need to better understand the energy budget of earth system.
- A coordinated model-data synthesis effort (multi-model, multi-methods such as the CORE effort of WGOMD) to improve past sea level reconstructions.
- Improve our understanding of present sea level changes and underlying causes.
- Identify forcing functions and separate natural and anthropogenic changes.

2) Future projections and predictions.

Climate model simulations of future regional sea-level changes due to anthropogenic climate change on multi-decadal timescales show geographical variability, which is substantial compared with the global-mean sea-level rise. The pattern of such future projections can mostly be explained by local temperature and salinity changes, i.e., they are steric in nature, but are likely to be caused by a combination of changes in surface heat and freshwater forcing, changes in redistribution by interior mixing, and trends in the wind-driven and thermohaline circulation. Future circulation changes may alter fundamentally the ocean-land ice interaction on regional and local scale. However, CMIP5 models are fairly coarse in spatial resolution, and a detailed understanding of the dynamics and impacts of regional sea level changes requires regional models with much higher resolution. Furthermore, inter-model differences in 21st-century projections reflect large uncertainties in (i) future evolution of climate modes, (ii) changes in regional and local ocean circulation, (iii) projection of glacier and ice sheet changes, (iv) interaction of the ocean with ice sheets.

Further progress requires

- A coordinated climate modeling effort (coupled ocean-ice or fully coupled climate) with enhanced representation of regional ocean dynamics, ice-sheet ocean interaction and impact of solid earth changes (land movement and geoid changes).
- Better understanding and reduction of uncertainties in climate models with respect to sea level.
- The test of coupled models against present day changes and processes and the addition of missing processes and components into climate models (e.g., ice sheet dynamics and ice sheet mass loss; changes in terrestrial hydrology; additional fresh water input from melting of glaciers).

3) An Integrated Approach

With respect to the solid Earth community, an important emerging issue is the uncertainty in Glacial Isostatic Adjustment (GIA) models. Emerging evidence indicates that regionally GIA models can be quite uncertain. Further improving those models however requires sea level feed back to be included because estimates of GIA depends on details of the land ice history (paleo information), which to a significant part appears to be influenced by ice sheet- sea level feedbacks not taken into account in the past. To make further progress we need to develop an integrated view of ice-sheet – sea level – solid earth interactions. There is the additional need to systematically account for coastal effects in future projections as well as non-climate related anthropogenic effects. This includes coastal and shelf dynamics and the inclusion of sediment and ground mining effects.

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Confidence and sensitivity of sea-level reconstructions

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Introduction

Reconstructions of historical sea level on the timescale of a few decades to slightly more than a century has been notably established, for example in Church et al. (2004) and Church and White (2011), using satellite altimetry from 1993 onwards to establish a calibration period for a model. From this calibration period, empirical orthogonal functions (EOFs) are obtained, the time-variable amplitudes of which are then constrained by tide gauge records. Thus, both historical mean sea level and regional distributions can be estimated. Minimum/maximum autocorrelation factors (MAF) (Switzer and Green, 1984) is a decomposition technique developed to isolate noise components from multivariate data, based on the assumption that the desired signal is spatially (or temporally) correlated with a shifted version of itself, while noise will generally be uncorrelated.

Model

As in Church et al. (2004), the amplitudes of each EOF are determined by employing a regularized optimal interpolation as described in Kaplan et al. (2000). However, in this preliminary analysis, the tide gauge data are represented by extracts from satellite altimetry, which allows the convenience of a vertical datum consistent between the calibration period and the "tide gauge" record. The unknown tide gauge datums are handled in Church et al. (2004) by using first differences of the time series, and in Ray and Douglas (2011) by solving for the datum of each gauge.

Analysis

For this analysis, 455 pre-selected tide gauge positions (from Church et al., 2004, selected for time series length and geodetic quality) have been used, in order to emulate a real reconstruction problem, though isolating the influences of tide gauge position and choice of calibration period. This analysis focuses on the influence of the character of the calibration period, and the resulting reconstruction error for various lengths of the calibration period. The influence of the prominent 1997/98 El Niño event has also been examined, showing a more Central Pacific El Niño-like pattern in the leading EOFs when excluding 1997/98 from the calibration period.

The error of the reconstruction with respect to known satellite altimetry for different lengths of the calibration period is shown in Figure 1. It appears that for calibration periods shorter than approximately 10 years, the error rapidly accumulates when moving away from the calibration, whereas the error seems largely stationary at a moderate level for longer calibration periods. This might be connected to the fact that all three reconstructions include 10 EOFs, and so may capture undesirable signals for the shortest period. To estimate the influence of geographical distribution, separate solutions have been made with only Northern Hemisphere and Southern Hemisphere gauges, respectively, see Figure 2. The MAF technique has been very preliminarily studied for this project, recovering some ENSO-like patterns, but with some work still needed to correctly handle masked-out areas in data grids.

Conclusions

The inclusion of a spatially uniform pattern (sometimes referred to as "EOF0") in the model basis has been found to be crucial in appropriately reconstructing global mean sea level, more so than the spatial distribution of tide gauges or the choice of the EOFs. This is in line with Christiansen et al. (2010), who also noted that the resulting performance is comparable to a simple arithmetic mean of the tide gauges; for improvement, they suggest using long-term climate simulations as an alternative way of obtaining the EOFs.

Regularization is of little concern for this preliminary analysis, since using actual altimetry data does not introduce the sparse coverage or possibly contradictory constraints of tide gauges. Indeed, it makes only a tiny difference in this study. In this case, limiting the choice of available to either hemisphere does not make much difference to the overall accuracy of the reconstruction; however, this study does not take into account the quality of the actual tide gauge data, only their spatial positions.

The MAF transform, while providing spatially "smooth" patterns, does not address the issue of missing data more than does the EOF. In addition, sea surface variability occurs on a variety of scales, including large-scale oscillation patterns like the ENSO and mesoscale phenomena, and any covariance across spatial scales may be poorly captured by the MAF transform.

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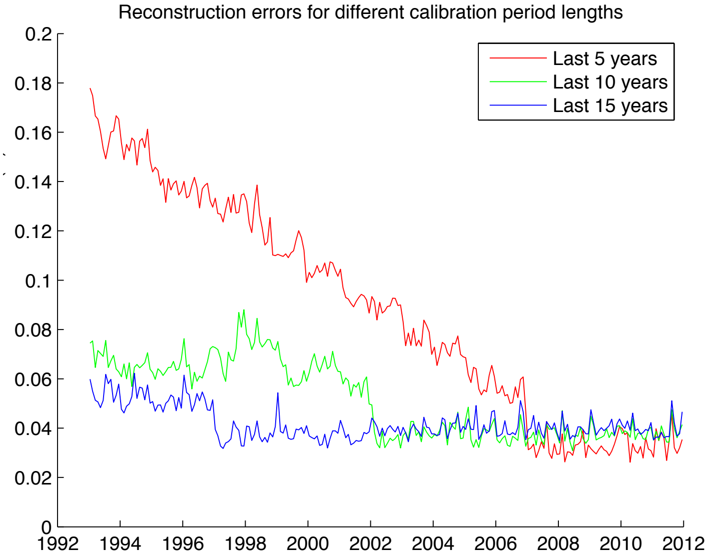

Figure 1: Global mean reconstruction error (with respect to satellite altimetry) for different calibration periods (shown in legend). All reconstructions shown include 10 EOFs in addition to an EOF0, and are fitted to the pseudo-tide gauges using an OLS fit. All tide gauge locations from the PSMSL database are used.

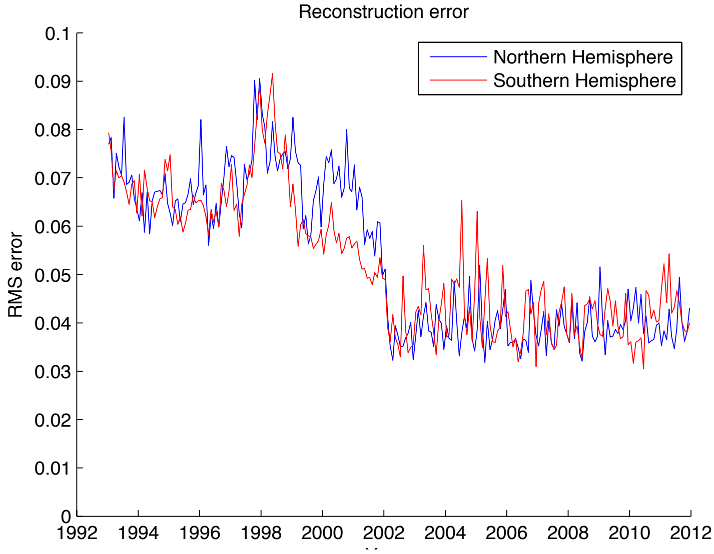

Figure 2: Global mean reconstruction error (with respect to satellite altimetry) for calibration patterns fitted to gauges only in the Northern or Southern Hemisphere, respectively. 364 of the 455 gauges used are in the Northern Hemisphere, while the remaining 91 are in the Southern Hemisphere. All reconstructions shown include 10 EOFs in addition to an EOF0, and are fitted to the pseudo-tide gauges using a Kaplan-based model.

Modeling Sea Level Rise and Ice Sheet Evolution using the Community Ice Sheet Model within the Community Earth System Model

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Introduction

Predicting future sea level rise requires comprehensive ice sheet models that can capture the important dynamics within the ice sheet. In addition, such an ice sheet model must be coupled with an Earth System Model to address the response of the ice sheets to future changes in forcing, including both the surface mass balance and melting due to ocean waters reaching the ocean-ice shelf interface. This brief note describes recent progress in developing the Community Ice Sheet Model (CISM) and coupling this model within the Community Earth System Model (CESM). A broad set of activities is described, including ice sheet dynamics, subglacial hydrology, surface mass balance and ocean-ice shelf coupling.

The Community Ice Sheet Model (CISM)
The CISM effort is focused on developing an ice sheet model suitable for use within coupled climate models for projections of future sea level rise. Initially, CISM started with the Glimmer model that simulated ice sheet dynamics based on the shallow ice approximation on uniform, rectilinear grids (Rutt et al. 2009). Initial development focused on coupling Glimmer with the CESM model (see below).

More recently, the dynamics of the model has been upgraded to a higher-order approximation to the full Stokes model, namely the first-order scheme of Blatter and Pattyn (2003). Improved solvers and domain-decomposition based parallelism were also implemented to allow for efficiency on larger computational grids and at higher resolution (Lemieux et al. 2011; Evans et al. 2012). This higher-order, parallel implementation of CISM formed the basis for simulations that were included in the SeaRISE (Bindschadler et al. 2013) and Ice2Sea (Edwards et al. 2013a; Edward et al. 2013b; Shannon et al. 2013) intercomparison efforts. Model output compares reasonably well with observed ice flow and, when perturbed with observational time series of changing ice flux, with observed ice sheet elevation changes (Price et al. 2011).

Current projects are developing new dynamical formulations on variable-resolution horizontal grids. Variable-resolution approaches enable focused resolution to capture important processes on ice streams and outlet glaciers, at ice sheet margins, and near grounding lines - areas where most of the dynamic changes occur - while utilizing coarse resolution elsewhere. Two different formulations are currently being developed. The first uses the Model for Prediction Across Scales (MPAS) framework that is built on Spherical Centroidal Voronoi Tessellations (SCVT) of the sphere (Ringler et al. 2008). This SCVT framework is an unstructured horizontal grid that is also being used for both ocean (Ringler et al. 2013) and atmosphere (Skamarock et al. 2012) component models. Grid resolution is determined by a density function that focuses resolution where needed (currently mesh refinement is static). A prototype model solving the first-order momentum balance (Perego et al. 2012) has been built on this MPAS framework and is currently being tested. Additional work is in progress to implement a new variational scheme (Dukowicz et al. 2011) as well as a nonlinear Stokes solver (Leng et al. 2012; Leng et al. 2013) within the MPAS framework.

A second approach uses adaptive mesh refinement quadrilateral grids by subdividing cells. This formulation is based on the CHOMBO (Colella et al. 2000) framework. Recent work with a two-dimensional, first-order accurate version of the model is showing promise in accurately capturing ice sheet dynamics at grounding lines of marine ice sheets, like in West Antarctica (Cornford et al. 2013). A full Stokes solver is also being developed with this framework.

While the above formulations will provide better representations of ice flow, the basal hydrology will also impact ice dynamics. The initial model had a basic basal sliding parameterization, but recent developments have introduced a new model with explicit representation of evolution within the basal hydrological system. This new model allows for two-way coupling between the subglacial hydrology and ice sheet dynamics. The new model accounts for the opening and closing of subglacial cavities in response to melt opening, creep closure and flow over bumps, as well as a representation of channelized subglacial flow, following Hewitt (2011). Together with a Coulomb friction sliding law (Schoof 2005), a full two-way coupling of ice sheet dynamics with the basal hydrology has been achieved (Hoffman et al. 2012).

Coupling within CESM

As mentioned previously, including an ice sheet model within a full Earth System Model enables the exploration of the interactions with other components and under different climate change scenarios. This is especially important for the ocean-ice shelf feedbacks and for computing the surface mass balance. We are in the process of adding CISM as an additional interactive component within the CESM, a fully coupled Earth System Model developed jointly by the US Department of Energy and National Science Foundation. We have performed some simulations with the existing system to gauge the ability of the model to simulate the historical surface mass balance over the Greenland Ice Sheet (Vizcaino et al. 2013a, Figure 1) and assess the future surface mass balance and dynamic response of the Greenland Ice Sheet to future climate change (Vizcaino et al. 2013b, Lipscomb et al. 2013).

Figure 1

One of the benefits of using CISM within CESM is that the surface mass balance calculations leverage the detailed surface flux computations that are part of the Community Land Model (CLM). For this reason, we have separated the surface mass balance computations from CISM and instead receive surface mass balance computations directly from

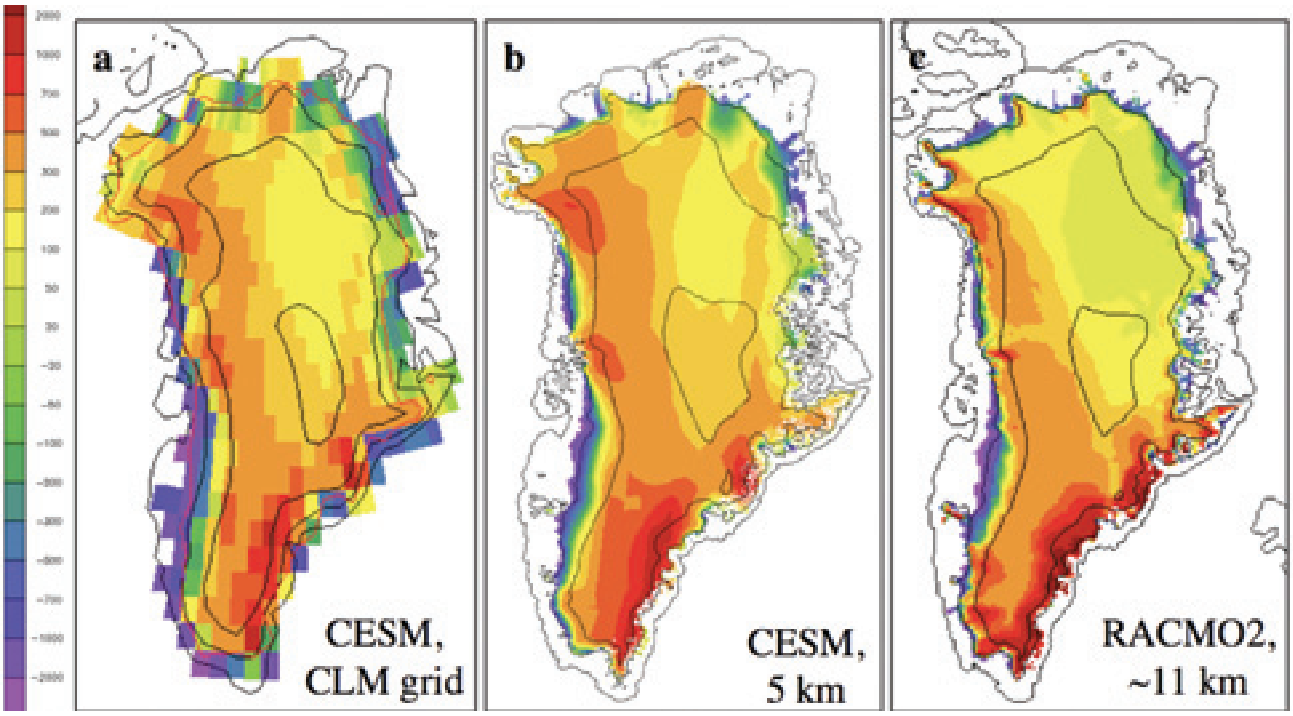

Figure 1. Surface mass balance from a coupled global CESM-CISM simulation showing (a) the SMB computed at the coarse (1-degree) CLM land grid and (b) interpolated to the fine resolution (5km) Greenland grid. These are compared to a fine resolution (11km) result from the regional RACMO model.

CLM. In particular, CLM computes the mass balance on a coarse grid cell, but based on multiple elevation classes. These calculations provide energetic consistency, capture important subgrid surface mass balance features, and are able to communicate albedo changes back to the atmosphere model.

In the future, CLM will utilize dynamic land units as a mechanism for tracking surface changes more accurately as the ice sheet extent changes. Work is also ongoing to incorporate remaining unresolved ice-atmosphere-land coupling mechanisms into the CESM, such as allowing the atmospheric model (CAM) to respond dynamically to ice sheet geometry changes. In addition, progress has been made on generating restart conditions for the coupled-ice sheet/climate model that contain a self-consistent internal history of simulated past climate change (Fyke et al. 2013). Soon, a new version of CISM with higher-order dynamics and these coupling improvements will be included in CESM and will become part of the standard CESM releases. Initial evaluations have also been carried out to determine the ability of CESM to simulate SMB over small glaciers, in preparation for the coupling of statistical glacier models into the coupled model architecture (Radic et al., 2012).

The ice-ocean interface has required significant changes to both the ocean and ice sheet component models. On the ocean side, the Parallel Ocean Program (POP) previously supported only a free surface upper boundary condition. A new vertical coordinate scheme was introduced based on the z* formulation of Adcroft and Campin (2004) that allowed the vertical coordinate to depress in response to the surface pressure. In addition, a solid upper boundary (i.e., the base of an overlying, floating ice shelf) is now supported using partial top cells (Losch, 2008), which more smoothly represent the ice shelf base. The approach is similar to the use of partial bottom cells for representing ocean bottom topography. Since most grids for climate simulation effectively treated ice shelves as land, new ocean bottom topography data sets that included ocean cells and bottom topography under large ice shelves were created from the Bedmap2 data set (Fretwell et al. 2012). We have performed initial simulations with these changes but using a fixed ice shelf geometry (also from Bedmap2) in a high-resolution POP configuration (see Figure 2). For a dynamic ice-ocean boundary, an immersed boundary method is being implemented and tested; a boundary layer scheme has also been added to POP for use at the interface.

Figure 2

The ice sheet model required a number of improvements for ice shelf simulation. In addition to appropriate ice shelf boundary conditions for ice sheet dynamics, the ice model counterparts to the ocean model changes above (e.g. immersed boundary method, fluxes of heat and water across the interface) are in progress. The ice sheet model also requires a better representation of ice front advance and retreat through iceberg calving laws. A recently described method for treating the ice advance at the calving front (Albrecht et al. 2011) has been implemented in a version of MPAS and initial results are promising. A number of calving laws are available and will be evaluated together with this new formulation.

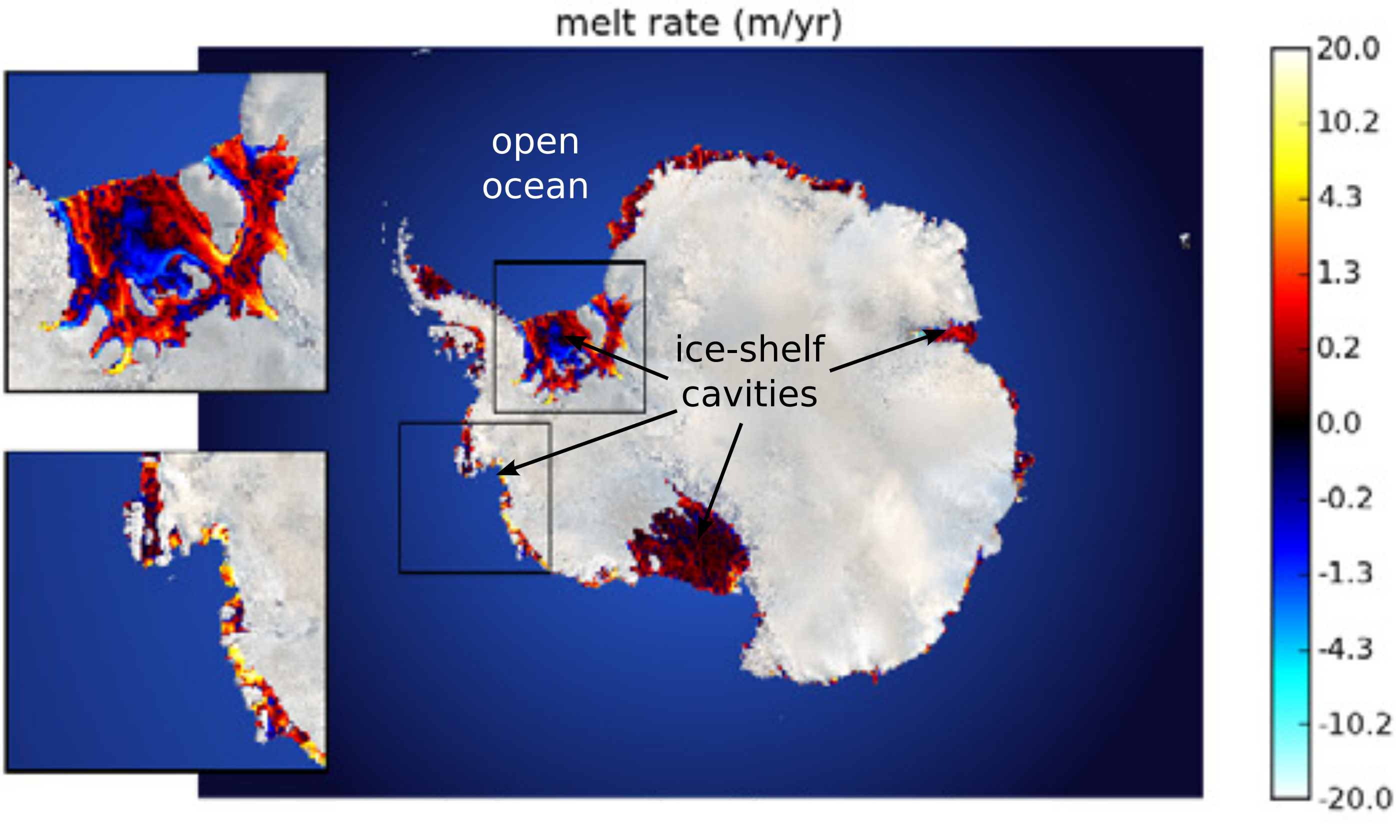

Figure 2. Melt rate (m/yr) at base of ice shelf for a high-resolution (0.1°) ocean simulation with Bedmap2 bottom topography and a fixed ice shelf geometry.

Summary

Significant progress is being made on a number of fronts to improve the representation of ice sheets within Earth System Models and our ability to provide better projections of future sea-level rise. A new release of the CISM model is planned for 2013 and additional improvements to CISM will be included in future CESM releases.

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An assessment of global and regional sea level in a suite of interannual CORE-II simulations: a synopsis

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Motivation to study sea level in CORE-II simulations

There are a growing number of observation-based measures of sea level related patterns with the advent of the Argo floats (since the early 2000s) and satellite altimeters (since 1993). These measures provide a valuable means to evaluate aspects of global model simulations, such as the global ocean-sea ice simulations run as part of the interannual Coordinated Ocean-ice Reference Experiments Griffies et al. (2009), Danabasoglu et al. (2013). In addition, these CORE-II simulations provide a means for evaluating the likely mechanisms causing sea level variations, particularly when models with different skill are compared against each other and observations. We have conducted an assessment of CORE-II simulations from 13 model configurations Griffies et al. (2013), with a focus on their ability to capture observed trends in ocean heat content as well as the corresponding dynamic sea level over the period 1993-2007. Here, we provide a synopsis of the assessment.

The CORE-II simulations are designed primarily for studies of interannual variability (Doney et al., 2007, Large and Yeager, 2012). The atmospheric state of Large and Yeager (2009), used as part of the CORE-II air-sea flux calculations, contains interannual satellite-based radiation only after 1983. Over the 15 year period from 1993-2007, observed sea level variations have a large component due to natural variability e.g., Zhang and Church (2012), Meyssignac et al (2012). The CORE-II simulations thus provide a useful means to evaluate interannual variability in ocean-ice models against observations of sea level.

A notable limitation of our study is that we are not focused on sea level changes associated with melting land ice. There are complementary global model studies that consider the ocean's response to melt events (Gerdes et al., 2006, Stammer (2008), Weijer et al., 2012 and Lorbacher et al, 2012). However, there are large uncertainties with rates of observed liquid and solid runoff from Greenland and Antarctica, thus prompting us to focus on steric aspects of global and regional sea level variations.

Questions asked by the CORE-II sea level study

Ocean warming causes ocean volume to increase due to a decrease in density. According to Church et al. (2011), such changes in global mean thermosteric sea level determine about one-third to one-half of the observed global mean sea level rise during the 20th and early 21st centuries. Although limited largely to examinations of natural variability over the relatively short period of 1993-2007, our assessment is of use to determine the suitability of global ocean-ice models for capturing the longer term trends that are the focus of studies such as Church et al. (2011), and of great concern for climate impacts from anthropogenic warming. In particular, we can assess the ability of models to respect observed changes in global ocean heat content and associated sea level trends, as well as regional patterns of sea level change due to ocean dynamics.

With this motivation, we focus the assessment on two general questions:

- Do CORE-II global ocean-ice simulations reproduce the observed global mean sea level variations associated with thermosteric effects estimated from the observation-based analyses? To address this question, we focus on ocean heat content trends, and how these trends are associated with changes in thermosteric sea level.
- Do CORE-II ocean-ice simulations reproduce observation-based changes to dynamic sea level patterns? To address this question, we partition dynamic sea level trends into their halosteric and thermosteric patterns, as well as bottom pressure contributions.

Results and discussion

As part of our synopsis, we present patterns from the CORE-II ensemble mean from the suite of 13 models analyzed by Griffies et al. (2013), where again all results are computed over the years 1993-2007. Where available, we compare CORE-II simulations to observation-based analyses. We also exhibit time series of global volume integrated upper ocean heat content and thermosteric sea level.

1. Time mean and anomalous dynamic sea level

We show the time mean dynamic sea level in Figure 1 (Front cover image), both from the CORE-II simulations and from the satellite-based analysis from AVISO (Archiving, Validation, and Interpolation of Satellite Oceanographic Data) LeTraon et al. (1998), Ducet et al. (2000). The models cluster around a global root-mean-square difference from AVISO between 0.09-0.15 m, with the ensemble mean having an RMS difference of 0.10 m. The models generally are more consistent with observations in the lower latitudes, with the high latitudes leading to larger differences, particularly in regions of mode and deep water formation (40-50 degrees latitude) as well as western boundary currents in the Atlantic and Pacific. The north-south gradient of dynamical sea level accross the Southern Ocean is weaker for many of the simulations relative to AVISO, perhaps suggesting a fluctuation towards a weaker than observed zonal transport in the Antarctic Circumpolar Current, or perhaps a shift in the overall latitude of the current. In general, we conclude that each of the CORE-II simulations produces a respectable 1993-2007 time mean dynamic sea level, meeting or surpassing the accuracy of the historical simulations considered as part of the CMIP3 analysis of Yin et al. (2010).

2. Linear trend in heat content and thermosteric sea level

As shown in Griffies et al., (2013), the linear trend in CORE-II simulated dynamic sea level over years 1993-2007 is dominated by the trend in steric sea level, with changes in bottom pressure (column mass) roughly an order of magnitude smaller. To illustrate changes in the steric patterns, we show in Figure 2 the linear trend in heat content per unit horizontal area as computed over the upper 700 m of ocean, and the corresponding trends in thermosteric sea level. The thermosteric trends largely reflect the heat content trends, but with some modulation from the thermal expansion coefficient. We compare these trends to those found in observation-based analyses.

We note that the two observation-based analyses themselves have differences, particularly in the North Atlantic, where Domingues et al. (2008) show much less warming than Levitus et al. (2012), and the Southern Ocean, where Domingues et al. (2008) show a cooling absent from Levitus et al. (2012). To the leading order, models capture the observed warming of the central-west Pacific found in both observation-based analyses, as well as the strong warming in the subpolar North Atlantic as found in Levitus et al. (2012). The models show a general cooling trend in the tropical northern hemisphere for the Atlantic and Pacific, with a westward extension in this simulated trend absent from both of the observational analyses.

The mechanism for the Pacific trend in the CORE-II simulations, with general rise in the west and fall in the east, accords with that discussed in such studies as Timmermann et al. (2010), Feng et al (2010), Bromirski et al. (2011), Merrifield et al. (2012), Zhang and Church (2012), and Meyssignac et al (2012), with these studies suggesting that the west-east gradient reflects the negative phase of the Pacific Decadal Oscillation. Likewise, the increased heat content in the North Atlantic over this period is dominated by natural variability. It is associated with a decrease in surface cooling in the subpolar region related to a change in the North Atlantic Oscillation (NAO) phase in the presence of a positive Atlantic meridional overturning circulation (AMOC) anomaly. Specifically, in the 1980s and early 1990s, the NAO exhibited a persistent positive phase and the associated large negative surface fluxes acted as a pre-conditioner for enhanced AMOC. During this period, enhanced poleward oceanic heat transport associated with an enhanced AMOC was largely balanced by surface cooling due to the positive NAO. Around 1995/1996, a reduction in the surface ocean heat loss associated with a change in the NAO to its negative (or neutral) phase allowed for the northward oceanic heat transport to cause the subpolar gyre to transition to an anomalously warm phase (e.g., see the discussion in Lohmann et al., 2009, Robson et al., 2012, and Yeager et al., 2012).

3. Evolution of global mean heat content and thermosteric sea level

For many purposes, the CORE-II simulations are relatively short, with the 60 years of CORE-II atmospheric state (1948-2007) repeated five times with an aim to reduce, although admittedly insufficient to eliminate, long-term drift in the deep ocean. Notably, the repeated 60-year cycle introduces a spurious periodicity, and it also leads to a lag in the response of the simulations to potential long term trends, such as the warming of the latter portion of the 20th century. Additionally, as discussed in Griffies et al. (2013), there is a slightly weaker linear trend in the CORE-II simulations relative to the observations, with this smaller trend in CORE-II revealed by the time series in Figure 3 for the global mean heat content and thermosteric sea level. Additionally, if we remove the linear trend, the variability in the CORE-II simulations correlates more to that in Domingues et al (2008) than to Levitus et al (2012).

Conclusions

There is a general agreement between the CORE-II simulated patterns of heat content change and thermosteric sea level change with the observation-based analyses. The global mean also shows a general agreement, though with a cool bias. These results lend confidence to both the observation-based analyses and the CORE-II simulations. Yet as with any model comparison project, one is perhaps left with more questions than answers, with this situation perhaps representing the real use of comparison projects. Namely, it is critical to identify relevant questions to make steps towards understanding as well as to improve numerical models and observation-based analyses.

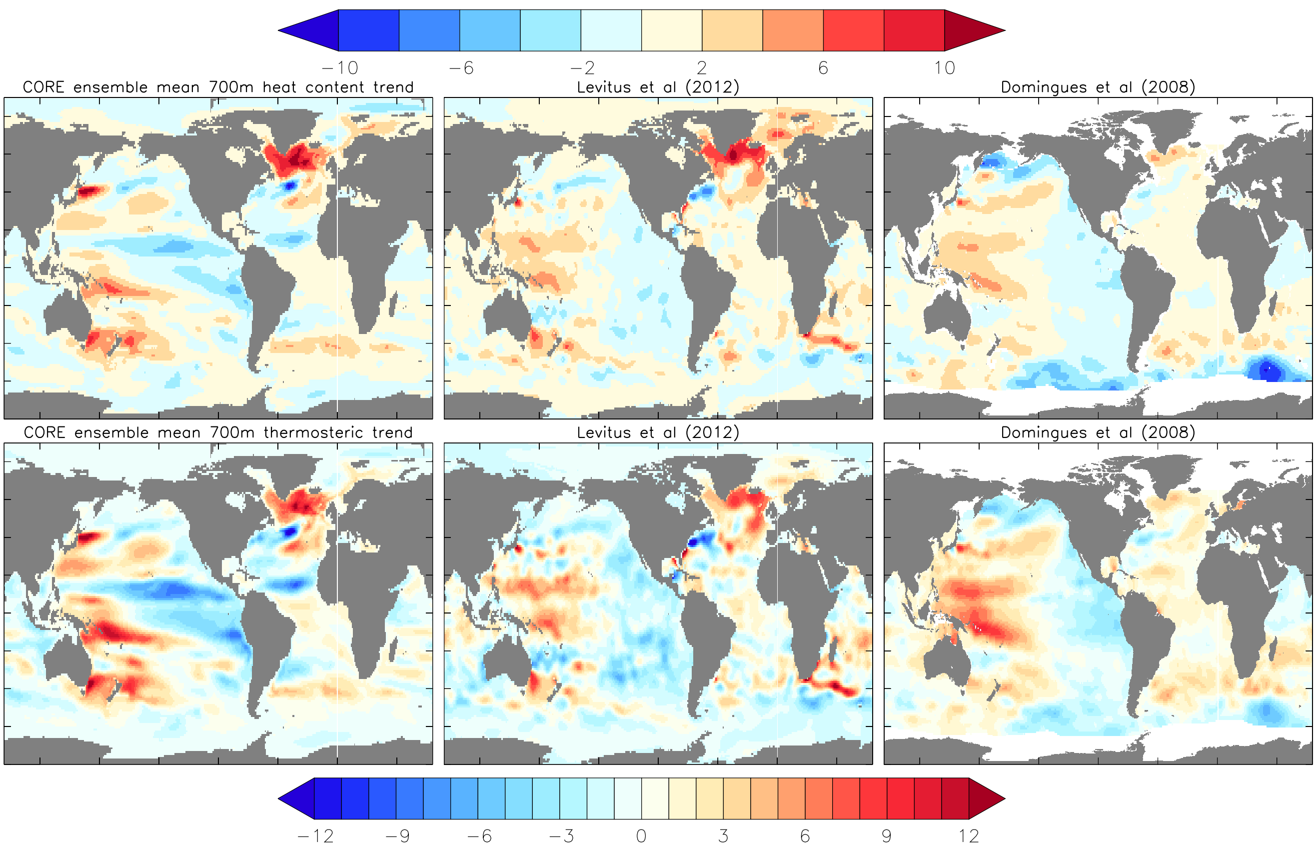

Figure 2: The upper row shows the linear trend in annual mean ocean heat content per unit horizontal ocean area as vertically integrated over the upper 700~m of ocean (W m^{-2}) for the years 1993-2007, computed from CORE-II ensemble mean as well as the observation-based analysis from Levitus et al. (2012) and an updated analysis from Domingues et al., (2008) and Church et al (2010) (see their Figure 6.3b). The lower row shows the corresponding trends in thermosteric sea level (mm yr^{-1}).

Model-model and model-observational differences may be due to model error, CORE-II atmospheric state errors, CORE-II experimental design limitations, and/or observational error or limitations Griffies et al. (2013). One avenue to make progress on these questions from the modelling perspective is to conduct detailed analyses of physical processes, term-by-term. We have in mind, for example, the analysis of Griffies and Greatbatch (2012), who decomposed the global mean sea level budget according to physical processes, as well as that from Palter et al. (2013), who decomposed the local steric sea level budget according to physical processes. Such analyses are nontrivial to perform with a single model, and logistically even more difficult across a suite of models such as the CORE-II simulations assessed here. Nonetheless, we contend that significant progress will be made to understand model-model, and to some extent model-observational, differences only when careful budget analyses are performed at the level of physical processes.

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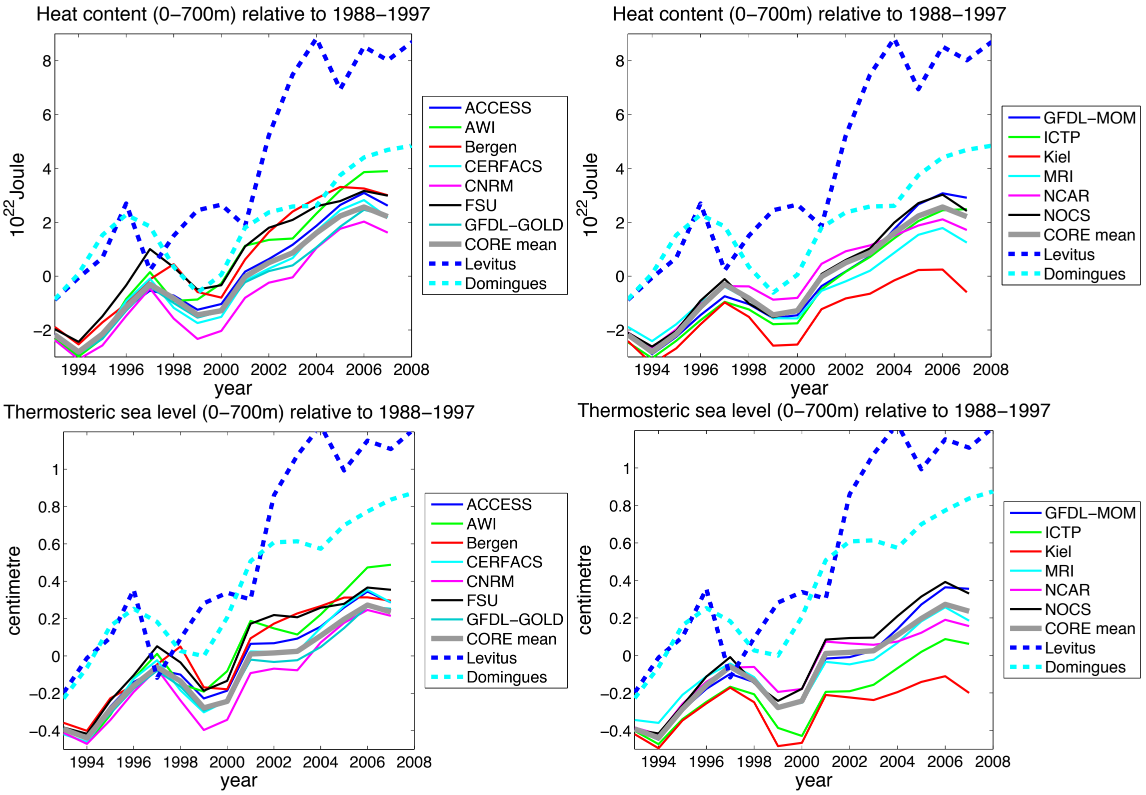

Figure 3: Time series for ocean heat content and thermosteric sea level integrated over the upper 700 m of ocean. To reduce dependence on a single chosen reference date, each result is computed with respect to the ten year mean for the respective model or observational time series, as computed over years 1988-1997. The CORE-II ensemble mean is also shown, as computed from all of the simulations. We also show estimates from observations based on analysis of Levitus et al. (2012} (global) and Domingues et al. (2008) (within the latitude range 65°S-65°N). Model results are global.

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Ocean Warming Around Polar Ice Sheets: Observation and Future Projection

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Introduction

The oceans play an important role in ice sheet dynamics. Significant parts of the Greenland and Antarctic Ice Sheet (GIS and AIS) directly interact with the oceans. In addition to the floating ice shelves and the marine-based AIS, the GIS is also in contact with the ocean through numerous outlet glaciers that terminate in deep fjords. These marine ices are sensitive to ocean temperature changes at their side and bottom interfaces. This is because water has very large heat capacity (3000-4000 times larger than air in terms of unit volume) and the oceans absorb and store most of the extra heat (more than 90%) induced by the enhanced greenhouse effect. It is therefore crucial to understand the mechanisms and quantify the magnitudes of ocean warming around Greenland and Antarctica.

The heat delivery to the seaward edge of polar ice sheets is influenced by both ocean transport and surface heat flux. In the upper 200 m ocean around Greenland, the East and West Greenland Current transports frigid polar water mass from the Arctic. These currents show less warming in future projections (Yin et al. 2011). Meanwhile, the Gulf Stream and North Atlantic Current transport a large amount of heat from low latitudes all the way to the subpolar oceans around Greenland. The intense heat release from the ocean to the atmosphere cools the warm subtropical waters before they reach the ocean/ice sheet interface, thereby protecting the GIS from marine melting. In the Southern Ocean, the strong and deep Antarctic Circumpolar Current (ACC) effectively prevents the subtropical-subpolar exchange and the poleward heat transport, thereby isolating Antarctica from other regions of the world. In the current climate, the oceans south of the ACC remain quite homogenous due to the strong vertical mixing induced by winds. So the extra heat can be quickly sequestered into the deep ocean without a direct impact on the AIS in the upper ocean. The important role of the ACC can be demonstrated from a paleoclimate perspective. Only after the opening of the Drake Passage and the establishment of the ACC at the Eocene/Oligocene boundary, could the AIS start to grow. The AIS has existed for many million years since then. Currently, the prevailing view is that the delivery of the relatively warm Circumpolar Deep Water (CDW) associated with the change of winds may be more important than the overall warming induced by diabatic heating in the ice sheet melt. The contraction and strengthening of the westerlies in the Southern Hemisphere can more easily send CDW onto the continental shelf, thereby impacting the ice shelves and AIS (Jacobs et al. 2011; Joughin and Alley 2011).

Observations during the Past Decades

In the North Atlantic subpolar gyre region around South Greenland, the upper ocean temperatures show significant variability and a cooling trend since the mid-1960s (not shown). The cooling was interrupted by an abrupt warming during 1995-1998 (Figure 1). Within 3 years the upper ocean temperature jumped from a cold state that had lasted for 2-3 decades to a very warm state until now. This suggests that some nonlinear/threshold behavior of the ocean-atmosphere system has been triggered and a rapid ocean regime shift has occurred in the northern North Atlantic (Yeager et al. 2012). How much of this ocean warming reflects natural cycles or a long-term trend is unclear. On one hand, the subpolar region around Greenland exhibits significant multi-decadal climate variability (Schlesinger and Ramankutty 1994). On the other hand, global warming shows polar amplification. Anyway, the recent warmth of the subpolar North Atlantic is quite unusual compared to the previous one during 1960s, in terms of its duration and magnitude. It extends from the surface to 1000 m depth with the largest magnitude in the upper 300 m (now shown). The significant ocean warming is confined to the south of the Greenland-Iceland-Scotland ridge. The magnitude around North Greenland is relatively small (Figure 1).

In addition to the ocean warming, other significant changes around Greenland have been observed subsequently, including sudden acceleration of the outlet glaciers of the GIS (Rignot and Kanagaratnam 2006), sharply increased mass loss from glaciers and ice cap in the Canadian Archipelago (Gardner et al. 2011), absence of the Labrador Sea deep convection except 2007-2008 (Vage et al. 2009), dynamic sea level rise in the North Atlantic subpolar gyre (Hakkinen and Rhines 2004), sea ice melt west of Greenland and in the Hudson Bay (Tivy et al. 2011), and pronounced hydrographic changes in the Labrador, Irminger and Iceland Seas (Yashayaev 2007). Given the large scale background warming, recent in situ ocean observations near the outlet glaciers of Greenland found that the warmer waters with subtropical origin can readily penetrate into the deep fjords in the subsurface layer, usually below 200 m (Straneo et al. 2010). These warm subsurface waters can cause strong basal melting and is likely responsible for the recent acceleration of the outlet glaciers.

Unlike the significant and overall ocean warming around South Greenland, ocean temperature around Antarctica shows small changes during the past two decades (Figure 1). It should be noted that ocean observation is sparse near the ice shelves and ice sheet. So the data may be associated with large uncertainty. The small temperature change is consistent with the observed Antarctic sea ice expansion, in sharp contrast with rapid sea ice melting in the Arctic during the recent decades. Although the Antarctic Ocean did not show a significant and overall warming, some recent observation near Pine Island glacier indicates that relatively warm CDW has penetrated onto the continental shelf region (Jacobs et al. 2011), likely induced by the poleward shift of the westerlies and stronger Ekman suction. The

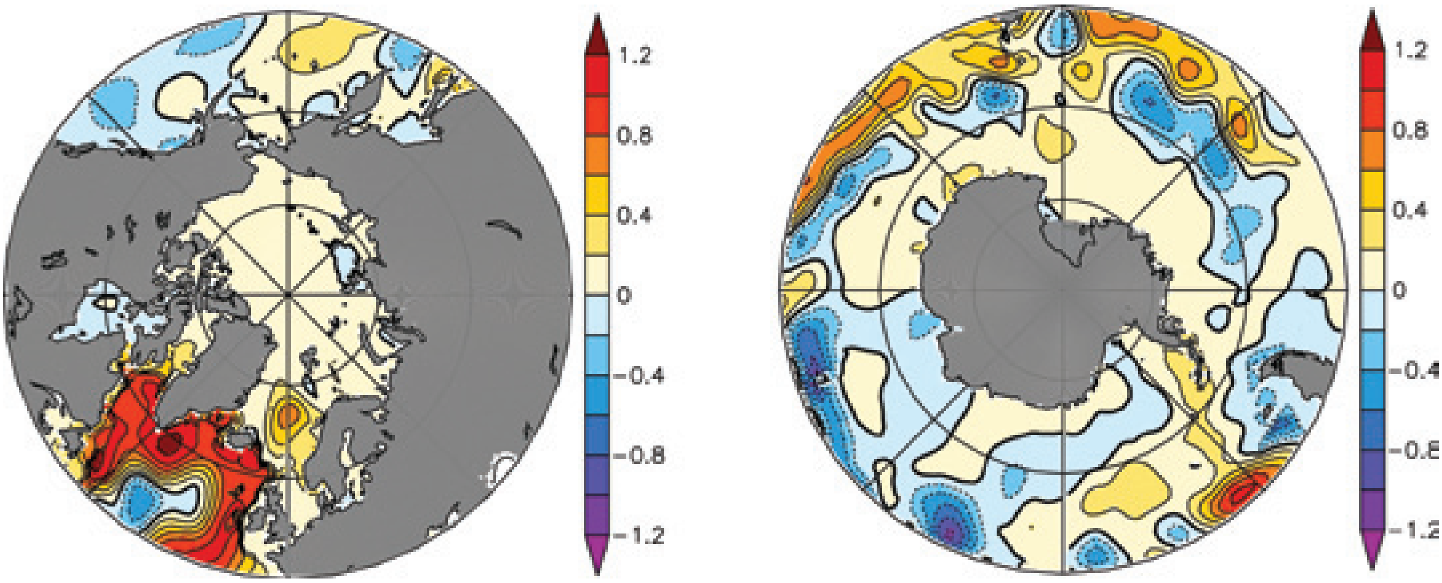

Figure 1. Linear trend (10^{18} J/year) of the ocean heat content in the upper 700 m during 1993-2011. The data is from the National Oceanographic Data Center (www.nodc.noaa.gov).

relatively warm CDW could eat away the submarine part of the glacier, thereby causing instability of the calving front and the acceleration of the glacier. In summary, the subsurface ocean layer is more important than the surface layer in ocean/ice sheet interaction (Joughin et al. 2012).

Future Projections

The future projections from 19 CMIP3 climate models indicate that the subsurface oceans around Greenland and Antarctica will warm in response to the increase in the greenhouse-gas concentrations during the 21st and 22nd century, but with differing magnitudes (Yin et al. 2011). According to the multi-model ensemble mean projections under the SRES A1B scenario, the subsurface layer (200-500 m) around Greenland will warm by 1.7°-2.0°C by the end of the 21st century. This warming is almost double the global mean in the same layer (~1.0°C). The subsurface ocean around Antarctica will warm by 0.5°-0.6°C, representing about half of the global mean ocean warming. Around both Greenland and Antarctica, the magnitude of the warming increases with time and the increase in external forcing. But their relative relationship with the global mean ocean warming remains roughly the same (i.e., double of the global mean around Greenland and half of the global mean around Antarctica). So the subsurface ocean warming shows a pronounced north-south asymmetry.

This asymmetry is also evident in the new CMIP5 results (Taylor et al. 2012), such as in the projections from the GFDL CM3 climate model under the RCP4.5 scenario (Figure 2). The magnitude and asymmetry of the warming are strongest in the highest emission scenario (RCP8.5). While most of the CMIP5 models performed 21st century projections, only a few of them extended the integrations to 2300. As an example, the subsurface ocean warming can be greater than 10°C by 2300 in the IPSL-CM5A-LR model projection, compared to 2-3°C warming around Antarctica (not shown).
The large subsurface ocean warming around Greenland is a result of the reduction of ocean surface heat loss, weakening of oceanic deep convection and the Atlantic meridional overturning circulation, and enhanced ocean vertical stratification. In response to the greenhouse-gas emissions, climate model projections suggest a faster warming of the atmosphere than the ocean and a reduction of the air-sea temperature differential in the high latitudes around Greenland. Without an efficient heat loss to the atmosphere, the heat transported from the low latitudes tends to remain in the subsurface ocean and circulate around Greenland, thereby causing melting at the ocean/ice sheet interface. By contrast, the strong wind-induced vertical mixing can limit the magnitude of the ocean warming in the Antarctic Ocean.

Projected anomalies with different magnitudes are usually associated with different levels of uncertainty. The CMIP3 model ensemble shows a wider spread in projecting the subsurface ocean warming around Greenland (Yin et al. 2011). This large uncertainty may be related to complex air-sea-ice interactions in the northern high latitudes around Greenland. For example, different models simulate different strengths and sensitivities and project different responses of the Atlantic meridional overturning circulation to external forcing. These differences can influence the magnitude of the projected ocean warming in different models.

Discussion and Future Work

Although significant advance has been made in recent years in both observing and modeling the subsurface oceans around Greenland and Antarctica, there are still great challenges. Compared to the surface ocean, it is more difficult to measure the subsurface ocean temperature change, especially near the ocean/ice sheet boundary. This difficulty and lack of long-term data in the critical regions has delayed our understanding of the ocean/ice sheet interaction and ice sheet dynamics. The development of state-of-the-art global or regional models helps study the ocean/ice sheet processes and guide the design of the observing system around Greenland and Antarctica. It should be noted that the CMIP3 and CMIP5 models are not

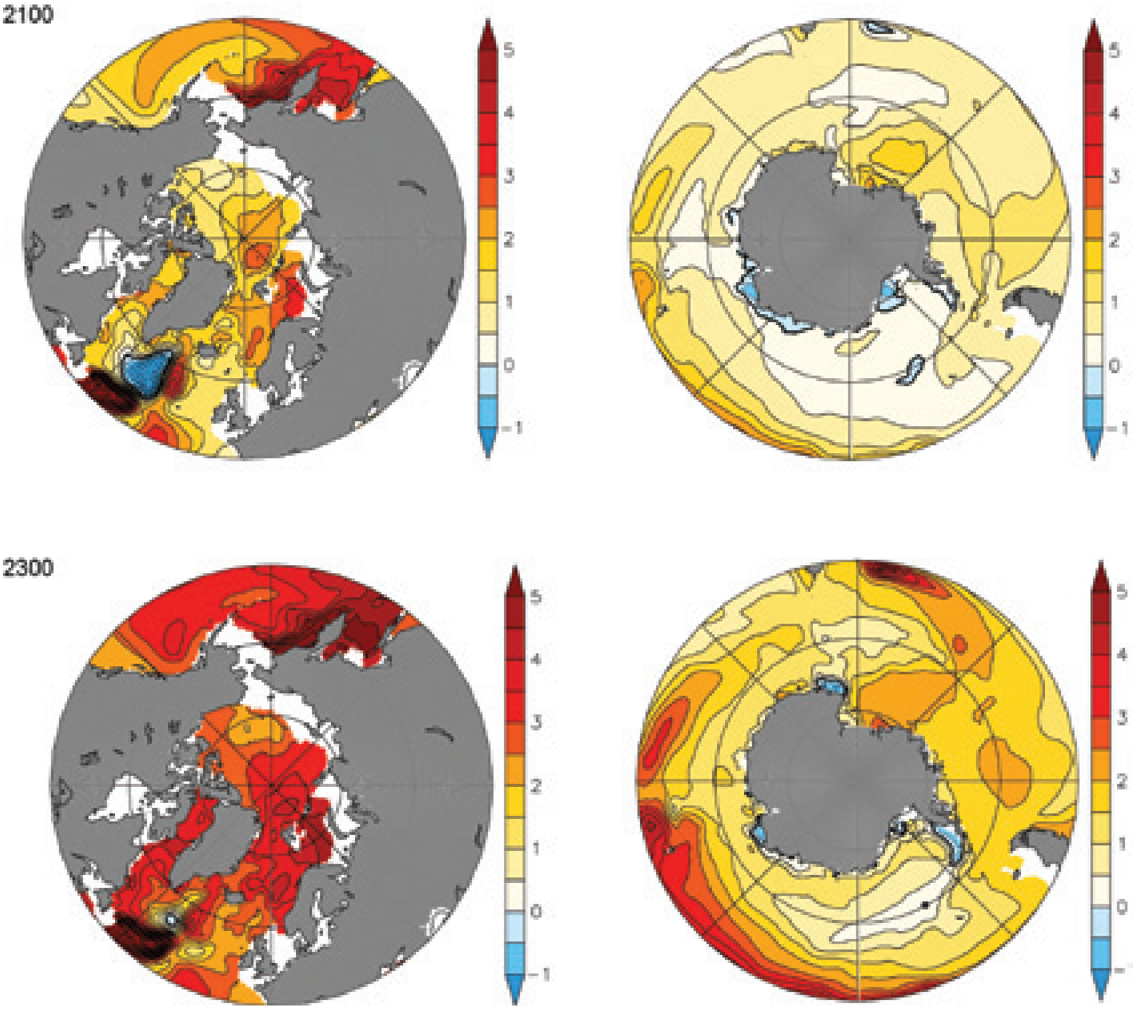

Figure 2. Projected subsurface ocean warming with the GFDL CM3 model and under the RCP4.5 emission scenario. Upper panels: projected anomalies of the ocean temperature in 200-500 m during 2091-2100 relative to 1986-2005. Lower panels: projected anomalies in 2291-2300 relative to 1986-2005. Unit: °C

particularly designed to study the ocean/ice sheet interaction. Due to the relatively coarse resolution (1°×1° for the oceanic models), the models cannot resolve narrow fjords around Greenland and the cavities beneath the Antarctic ice shelves. Given that the oceans may show enhanced warming in some particular and critical regions (Hellmer et al. 2012), it is necessary to develop high resolution global or regional models in which small scale features can be resolved. The incorporation of dynamical ice sheet models into climate system models is under way at modeling centers worldwide. Once ready, these sophisticated models would further advance our knowledge on the ocean/ice sheet processes, and help make more accurate projections of ice sheet evolution and global sea level rise.

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Anthropogenic forcing fingerprint on the observed tropical Pacific sea level trends from the CMIP5 simulations of the 21st century

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Introduction

Long term sea level rise is one of the most critical issues associated to global climate change because of its potential large impacts on coastal areas and low lying islands (Solomon et al. 2007, Nicholls et al. 2007). Since 1993, sea level rise is accurately monitored by satellite altimetry (using Topex/Poseidon, Jason 1-2, ERS 1-2 and Envisat) with high temporal resolution (1 week) and global coverage. The global mean sea level derived from satellite altimetry has been rising at a rate of 3.2 mm/yr during the last 2 decades. Altimetry data revealed that sea level is not rising uniformly but displays a strong regional variability (see Figure 1 and Meyssignac et Cazenave 2012), which has to be added to the global mean rise to give the total local sea level rise. This regional variability is essential for estimating the local sea level rise to assess potential impacts on vulnerable sites.

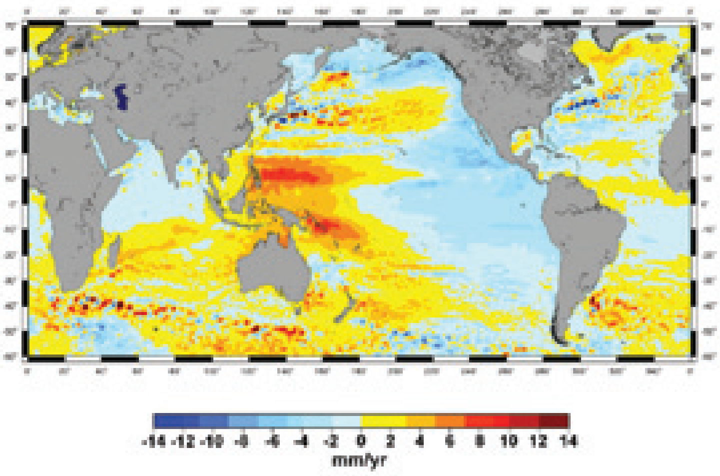

Figure 1: Satellite altimetry sea level trends over the period 1993-2010. Trends are computed from the weekly AVISO dataset. The global averaged sea level trend of 3.2 mm/yr has been removed.

Because of global warming due to anthropogenic Green House Gases (GHG) emissions, the upper ocean (above 700m) warms up and thus expands (Gleckler et al. 2012), mountain glaciers are melting (Huss et Bauder 2009) and ice sheets are loosing mass (Hanna et al. 2012). Combined together, these processes explain the fast global sea level rise observed by satellite altimetry since 1993 (Bindoff et al. 2007, Meyssignac et Cazenave 2012) and show the close relation that exists between anthropogenic GHG emissions and present day global mean sea level rise. At regional scale, our understanding of the origin and the causes of the observed sea level rise is more limited. It has been shown (with in-situ measurements and ocean models) that the regional variability in sea level trends observed by altimetry mainly results from ocean temperature and salinity changes (Ishii and Kimoto 2009, Levitus et al. 2012, Wunsch et al. 2007, Köhl et Stammer 2008, Lombard et al. 2009). Other phenomena such as the solid Earth response to the last deglaciation and the present ice mass loss, are also expected to contribute to the regional variability in sea level trends (Tamisiea and Mitrovica 2011. See also the recent review article by Stammer et al., 2013). But very few information is available in the literature on the role played by anthropogenic GHG emissions or other forcing of the climate system (solar activity, volcanic emissions, etc) on the regional sea level trend patterns.

Here we propose a first assessment of the fingerprint of the anthropogenic forcing on the sea level trend patterns observed by satellite altimetry since 1993. We focus on the Tropical Pacific region (noted TP hereafter) because it has experienced the largest regional variability in sea level trends over the altimetry era (since 1993, see Figure 1) and it is highly exposed to the risks associated to sea level rise (with many low lying islands in the western TP). This study is based on outputs from CMIP5 (Coupled Model Intercomparison Project Phase 5) models. It is an extension of a previous study based on CMIP3 models (Meyssignac et al. 2012b).

First we compare sea level trends from altimetry with sea level trends computed from a past 2-dimensional sea level reconstruction over the last 60 years (Meyssignac et al. 2012a). The objective is to determine how the TP sea level trend pattern observed by satellite altimetry changed with time and space over the recent past. Then, we analyse the multi-centennial control runs of 8 CMIP5 climate models that simulate the internal variability of the climate system. We show that the spatio-temporal variations of the TP sea level trend pattern are similar in observations and in these simulations that account only for constant natural forcing (solar and volcanic forcing) and constant anthropogenic forcing (anthropogenic GHG and aerosols emissions fixed at the pre-industrial value). In the last part of this study, we analyse the 20th century runs of the CMIP5 climate models extended over the 21st century with the RCP2.6 and RCP8.5 forcing scenario runs (The RCP2.6 and the RCP8.5 scenarios yield respectively to a mean global warming of 1.4° and 4.9° in 2100). These 200-year long runs (20th & 21st centuries) include the observed and projected anthropogenic forcing. By comparing them with the CMIP5 control runs we intend to identify the signature of the anthropogenic forcing on the TP sea level trend pattern. We show that in the observations of the recent past (altimetry and past 2D sea level reconstruction), this signature is hardly detectable above the large signal generated by the internal variability of the climate system. However, for the RCP8.5 forcing scenario, we show that the anthropogenic signature becomes well detectable for the 21st century.

Observations of the Tropical Pacific sea level trend pattern in the recent past

The satellite altimetry record considered in this study covers a period of 17 years between 1993 and 2010. Over this period, sea level trends show a characteristic ENSO-like pattern in the TP region (see Fig.1). This pattern has changed with time and space in the recent past (Meyssignac et al. 2012b, Stammer et al. 2013). To determine its spatio-temporal fluctuations over the last decades, we use a past 2D sea level reconstruction which estimates 2D sea level over 1950-2010 from a combination of tide-gauge records and statistical information on the dominant modes of regional variability from ocean models and altimetry data (Meyssignac et al. 2012a).

From the reconstruction, we compute TP sea level trend patterns over successive 17-year long windows (i.e. the length of the altimetry record considered here). Starting in 1950 and shifting the 17-yr window by one year, we compute fourty four 17-yr trend maps in the TP over the last 60 years. We do not show here the series of 44 TP sea level trend maps computed

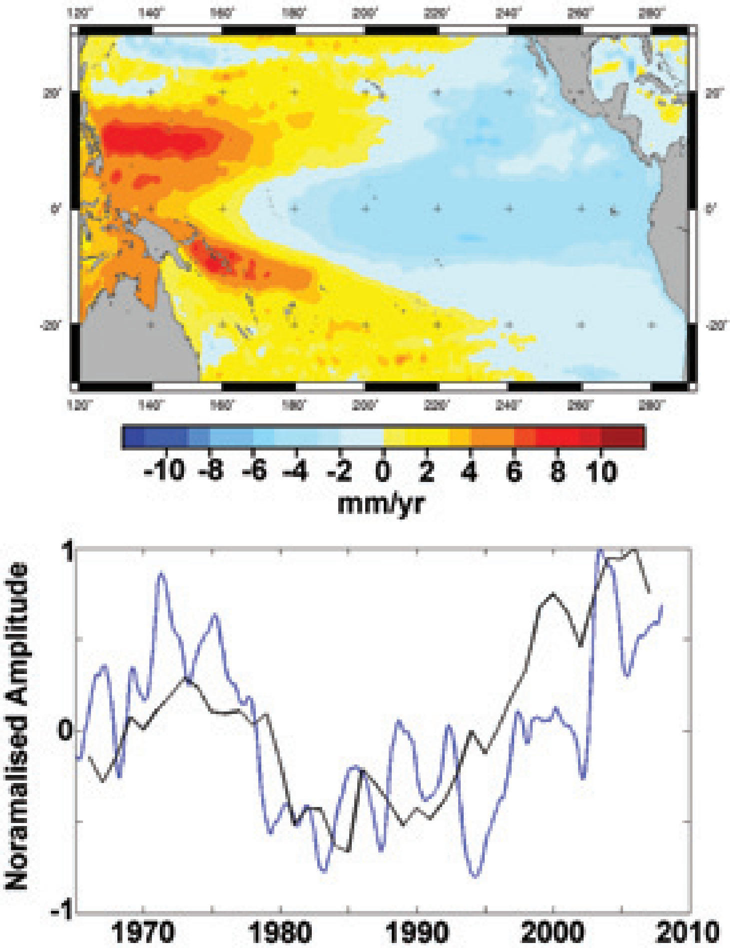

Figure 2: TP 17-yr sea level trend pattern that explains most of the variance (1st EOF, 62% of the total variance) among the past 44 TP 17-yr trend pattern computed from the past 2D sea level reconstruction. The black curve is the PC of the EOF and the blue curve is the niño3 index (with a 8 year smoothing)

from the reconstruction. But with an Empirical Orthogonal Function (EOF) analysis, we extract from this series the trend pattern that explains most of the variance (1st EOF). Figure 2 shows this dominant sea level trend pattern of the successive 17-yr windows and its associated Principal Component (PC). The sea level trend pattern on Figure is very similar to the TP trend pattern observed by satellite altimetry over 1993-2010 (on Figure 1). It explains more than 62% of the total variance of the series of 44 past sea level trend maps computed since 1950. This suggests that the TP sea level trend pattern we are observing now with satellite altimetry since 1993 is not unique but also existed in the recent past. It is actually the most characteristic 17-yr trend pattern of the last 60 years. The PC on Figure 2 shows that this pattern has fluctuated with time, with a minimum in the 1980s and a maximum at the end of the record, following a low frequency modulation of ENSO (indicated in Fig. 2 by the low-pass filtered Niño3 index). So the presently observed 17-yr sea level trend pattern in the TP is not steady with time. The comparison of the altimetry record with the past 2D sea level reconstruction indicates that it is actually the high stand of a low frequency fluctuation related to a low frequency modulation of ENSO.

Tropical Pacific sea level trend pattern in CMIP5 control runs

A similar analysis was developed with the multi-centennial control runs of 8 models of the CMIP5 project (see Table 1 for a description of the 8 models). In CMIP5 control runs, the external forcing is kept constant at its preindustrial value. The anthropogenic GHG and aerosols emissions are constant and fixed at their mid-19th century value. The solar activity and volcanic emissions are also kept constant along the run. These simulations provide an estimate of the internal variability of the climate system. As for the past 2D sea level reconstruction, we compute from each multi-centennial control run, the TP sea level trend patterns over successive 17-yr windows. With an EOF analysis, we extract the most common 17-yr TP sea level trend pattern of each control run and its associated PC. The resulting 8 TP trend patterns and their associated PCs give a statistical estimate of the 17-yr TP sea level trend pattern (and its temporal fluctuation) generated by the internal variability of the climate system.

The 8 TP trend patterns from the control runs are shown on Figure 3. The power spectrum of their respective PC is also shown on Figure 3 along with the power spectrum of the Niño3 index. On Figure 3, all control runs show a 17-yr TP sea level trend pattern that is ENSO-like as in the observations (see Fig. 2). Three control runs (CNRM-CM5, BCC-CSM1.1 and NCAR-CCSM4) show a 17-yr TP trend pattern very similar to the observations with two maxima located east of Papua-New Guinea and east of Philippines. The remaining models show a local minimum east of Philippines that is not in the observations (see Figure 2). For all control runs, the 17-yr TP sea level trend pattern fluctuates with time (see the peaks in the power spectrum of the PCs on Figure 3). These fluctuations follow a low frequency modulation of ENSO (see on Figure 3 how the peaks in the power spectrum of the PCs are in phase with peaks in the power spectrum of Niño3 indices). For 6 out of 8 control runs (GFDL-ESM2G, CNRM-CM5, ACCESS1.0, IPSL-CM5B-LR, NCAR-CCSM4 and HadGEM2-ES), these fluctuations are

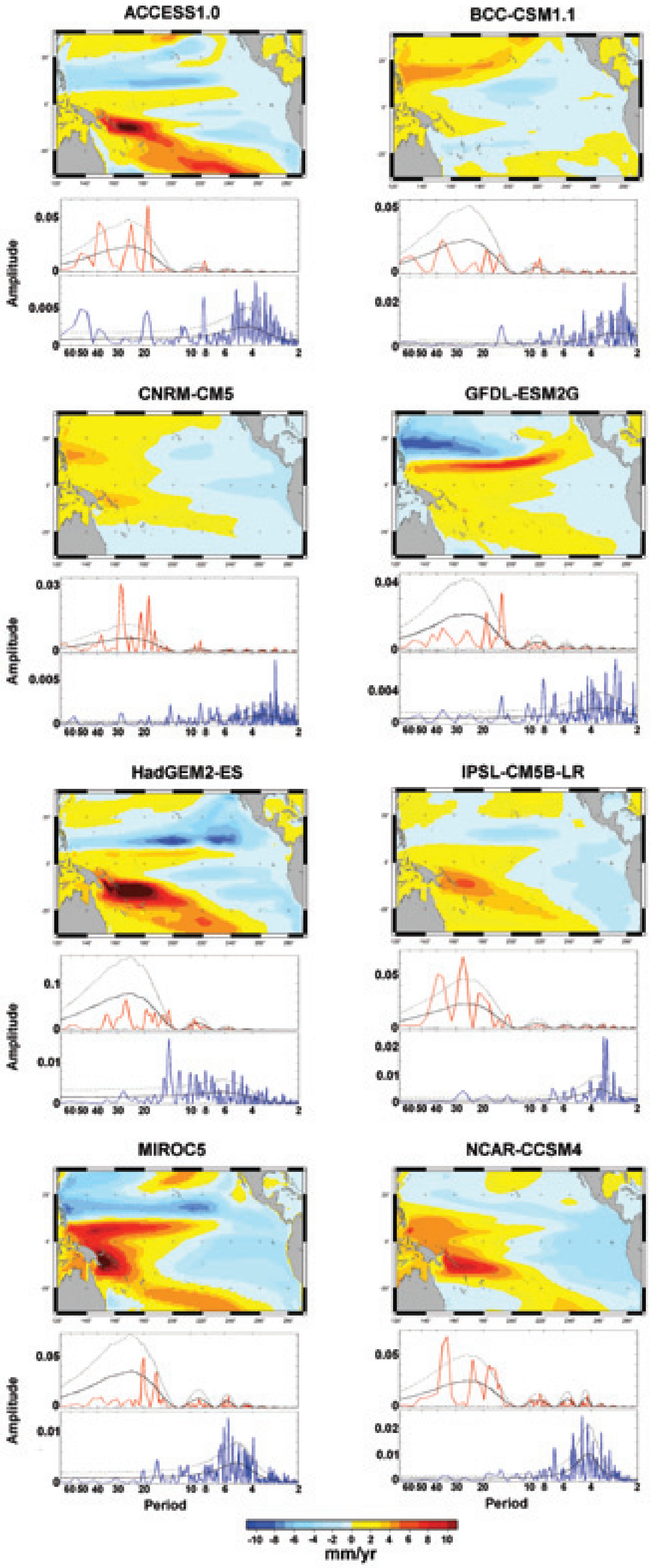

Figure 3: TP 17-yr sea level trend patterns that explain most of the variance among the 17-yr trend patterns computed from the control runs of the CMIP5 models. The power spectra of the PCs are plotted in red. The power spectra of the niño3 indices are plotted in blue. The grey dashed lines indicate the 95% confidence level above which peaks are considered statistically significant (the calculation based on a best fit AR2 process).

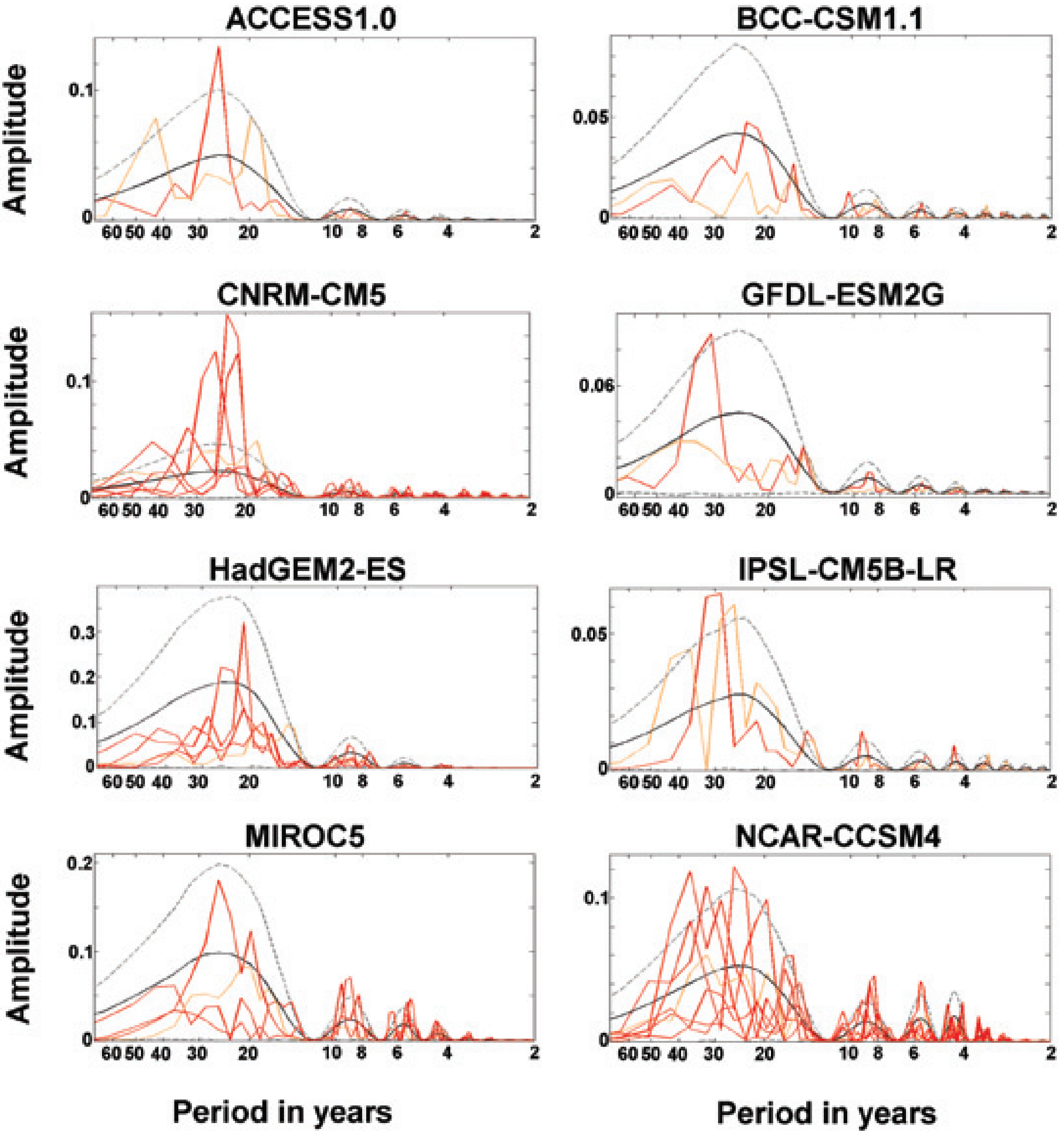

Figure 4: TP 17-yr sea level trend patterns that explain most of the variance among the 17-yr trend patterns computed from the RCP8.5 runs of the CMIP5 models. The power spectra of the PCs are plotted in red. Several PCs are plotted on the same plot when several RCP8.5 runs were available for a given model (cf table 1). The power spectra of the niño3 indices are plotted in blue. The grey dashed lines indicate the 95% confidence level above which, peaks are considered statistically different from the power spectra of the PCs of the respective control runs (the calculation is based on the control runs of Fig.3).

statistically significant (at the 95% confidence level). Thus, 17-yr TP sea level trend patterns in CMIP5 control runs are fairly similar to the observed 17-yr TP trend pattern since 1950. As in the observations, they fluctuate with time following a low frequency modulation of ENSO. This result shows that the internal variability of the climate system plays an important role in the TP sea level trend pattern observed today by altimetry (see Meyssignac et al. 2012b for more details).

It is also interesting to note that a majority of control runs (6 out of 8) shows some significant fluctuations of the TP 17-yr sea level trend pattern at periods between 19 and 22 years like in the observations (see Figure 2). But the observed record is actually too short (see PC on Figure 2) to extract a reliable period for the fluctuations and we can not be fully confident here that the TP 17-yr trend pattern fluctuate at the same period in the observations and in the control runs.

Tropical Pacific sea level trend pattern in CMIP5 simulations of the 20th and 21st centuries

Case of a low anthropogenic emission scenario for the 21st century (scenario RCP2.6)

Here we conduct the same analysis as before but with the 20th century runs of the CMIP5 models extended with the RCP2.6 scenario runs over the 21st century. These runs include the complete external forcing of the climate system (solar activity, volcanic emissions, anthropogenic emissions, etc). Over the 20th century the external forcing is based on historical records. Over the 21st century it follows the scenario of the CMIP5 project which simulates the lowest level of future GHG emissions (the RCP2.6 forcing scenario yields to cumulative diagnosed fossil fuel emissions of 182 Pg C over 2006-2100). When we extract from these runs, the 17-yr sea level trend pattern that explains most of the variance in the TP, we find patterns that are very similar to those computed from the control runs. We reach the same conclusion for the PCs. They do not differ significantly (at the 95% confidence level) between the 20th-21st century runs and their respective control runs. So, under the RCP2.6 low radiative forcing scenario hypothesis, CMIP5 models show that the external forcing of the climate system do not impact significantly the regional variability in 17-yr sea level trends over the TP. In particular this result implies that the regional variability in sea level trends that we are observing in the TP since 1993 with satellite altimetry, is largely dominated by the internal variability of the climate system. The impact of the external forcing whether natural or anthropogenic is still hardly detectable and still buried into the internal variability of the climate system in the TP region (see also Meyssignac et al. 2012b).

Case of a high anthropogenic emission scenario for the 21st century (RCP8.5 scenario)

Conducting a similar analysis with the 20th century runs of the CMIP5 models extended with the RCP8.5 high radiative forcing scenario (the RCP8.5 forcing scenario yields to cumulative diagnosed fossil fuel emissions of 1617 Pg C over 2006-2100), we obtain different results. Still, the 17-yr sea level trend patterns that explain most of the variance in the TP extracted from these runs are very similar to the patterns computed from their respective control runs (as for the RCP2.6 scenario). However, we find significant differences in terms of temporal fluctuations of the TP 17-yr sea level trend pattern. PCs associated to the 17-yr trend pattern present peaks that are significantly (at the 95% confidence level) higher in amplitude (by 80% on average) and lower in frequency (by 1/7 yr^{-1} on average) in the 20th-21st century runs than in their respective control runs (see Fig.4). So under the RCP85 high radiative forcing scenario hypothesis, CMIP5 models show that the external forcing, with high levels of GHG emissions, changes significantly the 17-yr sea level trends in the TP. It makes them more intense and it makes them fluctuate at a lower pace.

Summary

Satellite altimetry has revealed an intense regional variability in sea level trends over the 1993-2010 time span in the Tropical Pacific (with an ENSO-like pattern). Comparisons of the altimetry record with a past 2D sea level reconstruction since 1950 show that this intense regional variability in sea level trends is not unique over the past decades. Actually when we compute TP sea level trends over a moving 17-yr window starting in 1950 and ending in 2010, the TP 17-yr sea level trend pattern presently observed by satellite altimetry turns out to be the high stand of a low frequency fluctuation. Moreover it appears that this low frequency fluctuation is related to a low frequency modulation of the main natural mode of variability in the region: ENSO.

TP 17-yr sea level trend patterns computed from multi-centennial control runs of 8 CMIP5 models are very similar to the observed TP 17-yr trend patterns. In these control runs, which do not include anthropogenic GHG and aerosols emissions nor solar activity nor volcanic emissions, TP 17-yr trend patterns also fluctuate with time following a low frequency modulation of ENSO. This agreement between CMIP5 control runs and observations shows that the internal variability of the climate system plays an important role in the observed regional variability of TP sea level trends.

TP 17-yr sea level trend patterns computed from 20th century runs of the CMIP5 models extended over the 21st century with the RCP2.6 scenario, are also similar to the observed TP 17-yr trend patterns. Compared to control runs, these 20th-21st century runs include anthropogenic GHG and aerosols emissions at historical rates over the 20th century and at low rates over the 21st century in their external forcing. They also include the volcanic and the solar activity. But these extra sources of forcing do not generate significant differences on TP 17-yr sea level trend patterns, between these 20th-21st century runs and the control runs. So the impact of the external forcing variability whether of anthropogenic origin (GHG and aerosols emissions) or natural origin (solar and volcanic activity) on TP 17-yr sea level trend patterns is buried in the signal of the internal variability of the climate system. It is not detectable over the 20th century neither over the 21st century in the hypothesis of a RCP2.6 scenario. Accordingly, we conclude that the regional variability observed since 1993 by altimetry in the TP is actually dominated by the internal variability of the climate system. The fingerprint of anthropogenic emissions is still hardly detectable in this record.

20th century runs of the CMIP5 models extended over the 21st century with the RCP8.5 high radiative forcing scenario show different results. In this case the impact of the external forcing variability on TP 17-yr sea level trend patterns is clearly identified above the signal of the internal variability of the climate system. High rates of anthropogenic emissions make the regional variability of TP 17-yr sea level trends more intense over the 21st century and it makes it fluctuate at lower frequency with periods between 26 and 29 years (instead of 19 to 22 years). This suggests that the tropical Pacific may experience in the 21st century, longer periods of stronger regional variability in sea level rise than today.
This study based on most recent climate models from the CMIP5 project shows that the anthropogenic fingerprint is hardly visible in TP sea level trends observed by satellite altimetry (confirming earlier results based on CMIP3 models, see Meyssignac et al. 2012b) and that under high radiative forcing scenario for the 21st century, the anthropogenic fingerprint will become clearly identifiable in the future. The next step is to understand the dynamical processes that lead to such fingerprint on the TP sea level variability. To do so we need to analyze in details the influence of the external forcing on the TP sea level in climate model runs forced with anthropogenic forcing only. We will also need to analyze runs forced by the solar activity only and the volcanic emissions only in order to get a clear picture of the role played by each external forcing and unravel their respective impact on the observed and projected regional variability in TP sea level. This will be the subject of future investigations.

Acknowledgements

This work was supported by the Centre National d'Etudes Spatiales (CNES). Part of this study is based on observations from Topex/Poseidon and Jason-1 and 2 spacecrafts. The altimeter products used here were produced by Ssalto/Duacs and distributed by Aviso with support from CNES. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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Model	Modeling group	Simulation length (yrs)			
ACCESS1.0	CSIRO-BOM	1 Control run: 1 20th century run:	500 156	RCP2.6 run: 1 RCP8.5 run:	not available 95
BCC-CSM1.1	BCC	1 Control run: 1 20th century run:	400 156	1 RCP2.6 run: 1 RCP8.5 run:	95 94
CNRM-CM5	CNRM-CERFACS	1 Control run: 5 20th century run:	850 156	1 RCP2.6 run: 5 RCP8.5 run:	95 95
GFDL-ESM2G	NOAA GFDL	1 Control run: 1 20th century run:	500 145	1 RCP2.6 run: 1 RCP8.5 run:	95 95
HadGEM2-ES	MOHC-INPE	1 Control run: 5 20th century run:	576 146	4 RCP2.6 run: 4 RCP8.5 run:	95 95
IPSL-CM5B-LR	IPSL	1 Control run: 1 20th century run:	300 156	RCP2.6 run: 1 RCP8.5 run:	not available 95
MIROC5	MIROC	1 Control run: 3 20th century run:	670 156	3 RCP2.6 run: 3 RCP8.5 run:	95 95
NCAR-CCSM4	NCAR	1 Control run: 6 20th century run:	500 156	6 RCP2.6 run: 6 RCP8.5 run:	95 95

Table 1: Length (in yrs) of the runs of the 8 CMIP5 models used in this study.

Comparison of Steric Sea Level from an Ensemble of Ocean Reanalyses and Objective Analyses

Andrea Storto[1] and the CLIVAR/GSOP intercomparison Group

1) **Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC), Bologna, Italy**

During a recent CLIVAR/GSOP and GODAE meeting, a joint initiative among ocean synthesis producers was established in order to extensively compare some climate key parameters from global ocean reanalyses. The list of the parameters includes sea surface height, steric sea level, mixed layer depth, sea-ice variables, depth of the 20°C isotherm, air-sea fluxes, Atlantic meridional overturning circulation and ocean salt and heat content. More information on the comparisons is available on the websites https://www.godae-oceanview.org/outreach/collaborative-working/gov-gsop-clivar-private-pages and http://twiki.godae-oceanview.org/bin/view/Main/GOVGSOPCLIVARReanalysesIntercomparison.

CMCC is leading the intercomparison of the steric sea level (SSL), which is an important indicator of climate and global change. The scientific objectives of the comparison consist of i) quantifying the global SSL, its uncertainty and the reanalyses consistency and skill with respect to independent estimates; ii) assessing the regional SSL change and the agreement between the ocean reanalyses; iii) quantifying the relative contributions of the thermal and haline components and iv) quantifying the relative contributions of different vertical regions. We present here some preliminary results from the intercomparison exercise, which involved 20 products, of which 16 ocean reanalyses and 4 observation-only products, thus representing a major effort in evaluating the SSL provided by state-of-the-art ocean reanalysis systems. Data were provided as 1993-2009 monthly means on regular grid of 1 degree resolution. The complete list of the participating institutes may be found on-line within the conference poster (http://www.clivar.org/sites/default/files/WGOMD/activities/sealevel/posters/Storto_hobart.pdf).

The comparison strategy consists of a validation period (2005-2009) and an extended intercomparison period (1993-2009), the former covering the gravimetry era, while the latter the altimetry era. Within the validation period, the ocean synthesis products are compared with SSL estimates given by monthly means of altimetric sea-level anomaly minus gravimetric ocean bottom mass anomaly. For the total component (altimetry), gridded monthly maps of sea-level anomalies from AVISO were used, while for the ocean bottom pressure signal, the ensemble of the GRACE RL05 solutions smoothed with a 500 Km radius Gaussian filter were adopted (Chambers and Bonin, 2012). For the latter, the global effect of the atmospheric sea level pressure is estimated from the ECMWF ERA-Interim atmospheric reanalysis and removed from the fields. Glacial isostatic adjustment effects from Peltier (2004) are also removed. Additionally, an attenuation factor is used in order to recover from the smoothing effects of the GRACE data smoothing procedure.

For the validation period, it turned out that the Global SSL (GSSL) fluctuations are quite well reproduced by the reanalyses, its ensemble mean leading to an anomaly correlation of 0.83 with the independent satellite estimates; the seasonality of the GSSL is generally well reproduced while linear trends exhibit larger uncertainty and variability among the reanalyses. Interestingly, the ensemble of the ocean reanalyses is more skillful than the ensemble of objective analyses (i.e. observation-only products, with 0.80 correlation). It is also more skillful than any other individual products. This applies also to the regional SSL: in terms of area-averaged point-by-point anomaly correlation with the reference dataset, the ensemble of the reanalyses owns again a correlation (0.84) higher than any individual product (0.77 at the maximum) and the ensemble of the objective analyses (0.74). This latter feature is especially appreciable in areas with a poor observing network and/or impact of deep and bottom waters (e.g. ACC, Bering Sea). Figure 1 depicts the 2005-2009 map of temporal correlations between the ensemble of the reanalyses and the reference dataset (altimetry minus gravimetry), suggesting that there exist a very high consistency of the reanalyses ensemble with the verification dataset all over the Global Ocean, except in the Southern Ocean south of approximately 55S, where however the availability of data is incomplete. Thus, the ensemble mean proves a robust tool for further diagnostics. For the extended intercomparison period (1993-2009), the reanalyses ensemble shows a good consistency for the GSSL also with respect to previous works (e.g. Cazenave and Llovel, 2010 for a compilation of results), with a linear trend of 1.06 +/- 0.05 mm/yr and 1.19 +/- 0.05 mm/yr for the reanalyses and objective analyses ensembles, respectively. Generally, we found no consensus on the relative contributions of the thermal and haline components of the GSSL: while the halosteric contribution impact on the GSSL trend is generally neutral or slightly negative, there is no clear consensus on its contribution to the GSSL variability, its explained variance ranging from 50 to 95%; however almost all the products suggest that the halosteric component acts more on seasonal than interannual scales. Finally, we have assessed the contribution of the "unobserved ocean" (considered below 700 m for the 1993-2009 period), which accounts for the 20% of the interannual signal variability in the case of the reanalyses ensemble.

Future plans concern a deeper analysis and interpretation of the results, with the use of the statistical properties of the ensemble to quantify the significance of the results.

Acknowledgments

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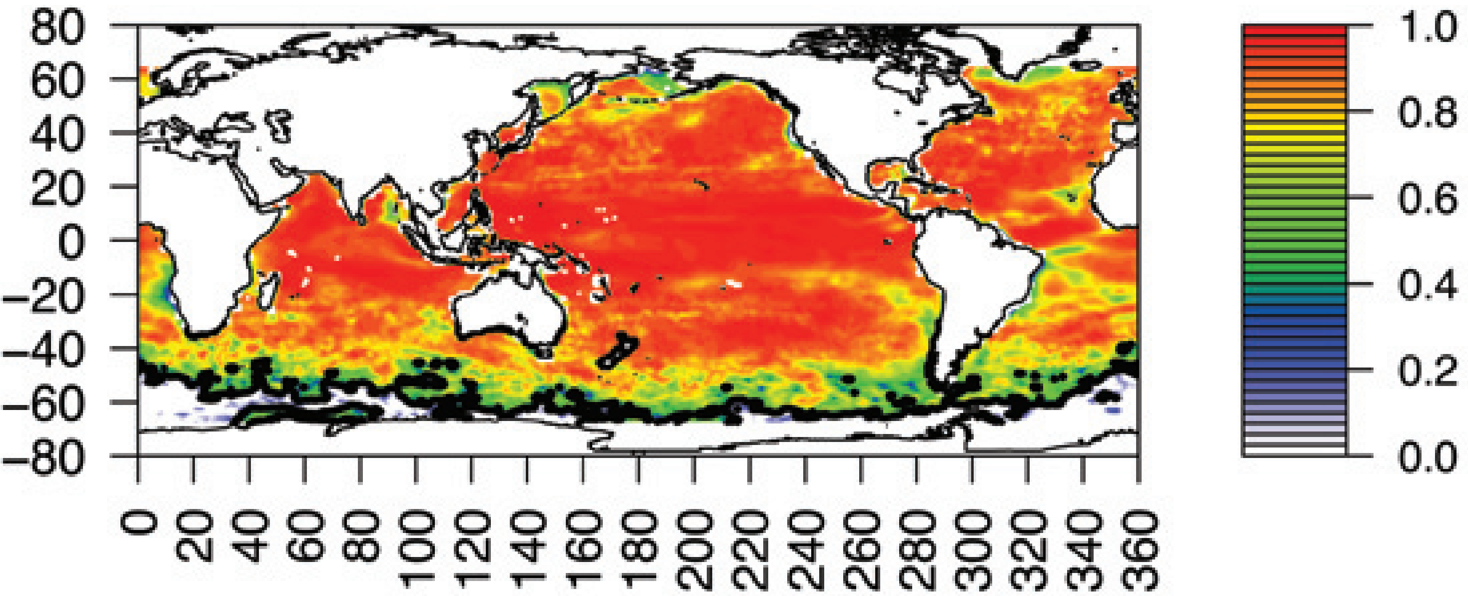

Figure 1. 2005-2009 Steric Sea Level Anomaly correlation between the reanalyses ensemble and the validation dataset (altimetry minus gravimetry) described in the text. The thick black line in the Southern Ocean defines the contour line in correspondence of the significance level (0.254 at 95% confidence level). Data north of 65N are missing.

Steric height, shelf mass loading and self attraction and loading in future sea level projections

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Introduction

Global sea level is rising (Church et al., 2011) and is expected to continue to rise on a multicentennial to millennial time scale (Li et al., 2013; Meehl et al., 2012; Yin, 2012). Due to a variety of complex and interconnected processes in the ocean, on land and in the atmosphere, the observed increase in global mean sea level shows large short-term variations and regional changes in sea surface height vary significantly (Cazenave et al., 2008). The rate of change in global mean sea level and regional differences superimposed on the long-term change are expected to continue in the future (Yin et al., 2010; Slangen et al., 2012; Yin, 2012). To accurately assess regional rates of changes in sea level it is important to quantify all processes that contribute to regional sea level variability.

We examine regional steric height changes and the shelf mass loading effect due to redistribution of ocean mass between the deep and shallow regions of the ocean in 21st century projections of a state-of-the-art atmosphere-ocean general circulation model. The magnitude of self attraction and loading (SAL) effects induced by the redistribution of ocean mass is then estimated. Since most of the shelf regions are found at high northern latitudes, the net effect is expected to be largest there. In a recent study, Gregory et al. (2012) estimated the SAL effect to vary from -4 to +14% of the global mean sea level rise due to thermal expansion. They do not, however, go into details as to how SAL effects are modeled.

Data and methods

Regional changes in ocean bottom pressure (OBP) and steric height are analyzed by using output from version one of the intermediate resolution version of the Norwegian Earth System Model, NorESM1-M (Bentsen et al., 2012; Iversen et al., 2012). NorESM1-M is based on the Community Climate System Model version 4 (Gent et al., 2011; Vertenstein et al., 2010), but utilizes an isopycnic ocean module. The ocean component of the model conserves mass (does not obey the Boussinesq, or constant density, approximation) and is therefore well suited to capture sea surface height changes associated with changes in the density of sea water, and to analyze changes in OBP. The model has a horizontal resolution of approximately 2° for the atmosphere and land components and 1° for the ocean and ice components.

We use model output from the three representative concentration pathway (RCP) scenarios RCP2.6, RCP4.5 and RCP8.5 (Van Vuuren et al., 2011) for the time period 2006–2100. The RCPs represent, in order, an emission scenario tailored towards the two-degree target (that the global mean temperature by 2100 should not exceed two degrees compared to the pre-industrial climate), an emission scenario with rather strong reductions in greenhouse gas emissions, and a business-as-usual scenario. In this study, results are presented for RCP4.5. The presented integrations are part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). The model output is corrected for climate drift by subtracting the linear trend from a pre-industrial control run (the latter with fixed composition of atmospheric greenhouse gases and aerosol particles) from the RCP runs. As shown in Bentsen et al. (2012), this trend is, in general, weak. Correcting for climate drift does not affect the results of this study (not shown).

Steric height is computed by vertical integration of the specific volume anomaly. To assess the redistribution of water masses within the world's oceans we compute the changes in ocean bottom pressure (OBP). Its units are mbar and here we employ the approximation 1 mbar ≙ 1 cm. Changes in atmospheric loading are not included in the OBP fields used in this study.

The OBP fields are further interpolated onto a 0.5-by-0.5 degree grid and used as input to a code that computes SAL effects by solving the sea level equation (Farrell and Clark, 1976) through a pseudo-spectral approach (Mitrovica and Peltier, 1991), including the effect of changes in the earth rotation (Milne and Mitrovica, 1998). In order to allow for the computation of the SAL effects due to ocean dynamics, we have modified the conventional approach to solving the sea level equation by complementing the load function (Eq. 12 in Mitrovica and Peltier (1991)) with a term representing OBP changes (Tamisiea et al., 2010). Note that in our approach the OBP fields are used as a static load, meaning that the resulting SAL effects will determine the equilibrium ocean configuration, but they are not coupled to the general circulation model. The solid earth is modeled as a spherically-layered elastic body, with densities and mechanical properties based on the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981). The solutions are truncated at spherical harmonic degree and order 360.

Results

Steric and ocean bottom pressure changes

Figure 1 shows the simulated changes in steric height between the first and the last decade of the RCP4.5 run for the entire water column (Figure 1c) as well as the upper (Figure 1a) and lower layer (Figure 1b). The global average change is 18 cm (13 and 28 cm for RCP2.6 and RCP8.5, respectively).

To further investigate the origin of the steric changes, we computed the contributions from different layers (Figure 1a,b). In

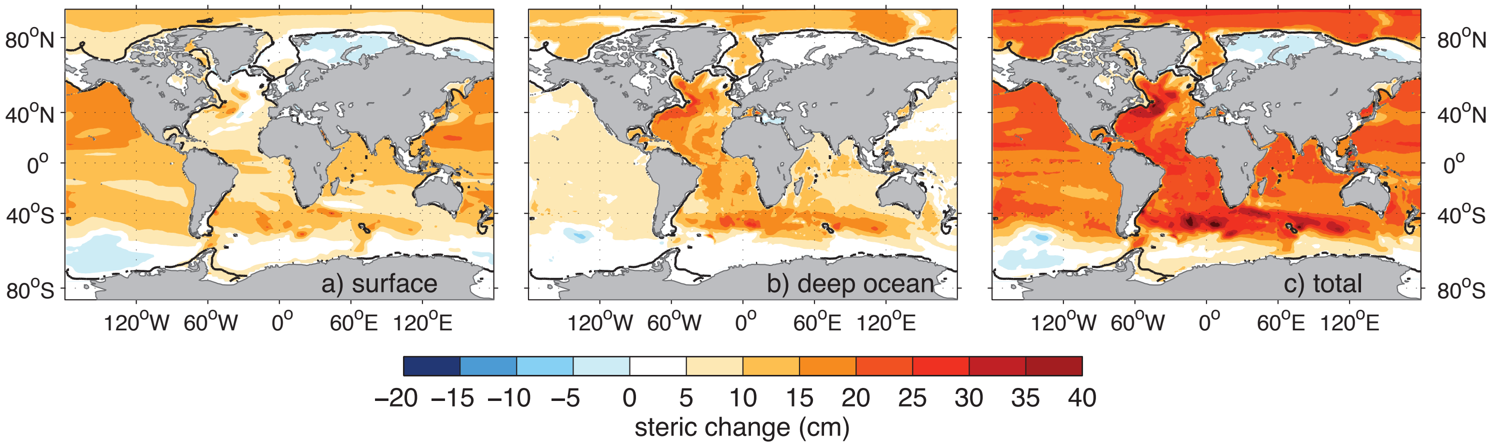

Figure 1. Change in steric height in the (a) upper 700 m, (b) the deep ocean below 700 m and (c) the entire water column from 2006–2015 to 2091–2100 in RCP4.5. The black line indicates the 700 m isobaths.

the Pacific Ocean, the contribution from the lower layer is very small compared to the upper layer. Most of the expansion is due to a net warming of the upper 700 m except in the northern North Pacific where freshening contributes about equally to the expansion (not shown). In the Atlantic Ocean as well as the Arctic Ocean the bulk of the steric height changes originates in the deep ocean (below 700 m).

In the North Atlantic Ocean, a pronounced warming takes place (Iversen et al., 2012) in both layers. However, in the upper layer the resulting expansion is largely balanced by a net salinification while, in the lower layer, thermal expansion is only partly offset by salinification (not shown). The rather small contribution of the upper layer to regional steric height changes in the North Atlantic is therefore not due to a weak warming as compared to the deeper layer, but to the more effective density compensation in the upper layer. Indeed, the upper layer is warming more strongly than the lower layer (Iversen et al., 2012).

The steric height changes exhibit considerable regional variations on top of the global mean steric height change (Figure 1c). The most striking feature is a strongly reduced sea level rise on the continental shelves compared to the ocean interior. The sea water expansion that takes place below the depth of ocean shelves, typically a few hundred meters, will induce a horizontal pressure gradient with elevated pressure over the deep ocean compared to the shallow shelves. This results in sharp cross-shelf gradients in steric sea surface height creating a horizontal pressure gradient with elevated pressure over the deep ocean compared to the shallow shelves. To balance this pressure gradient, water masses will flow from areas of larger water depths (ocean interiors) onto shallow continental shelf areas (Landerer et al., 2007; Yin et al., 2010). The resulting change in the water mass loading will be manifested as changes in OBP.

Figure 2a displays the change in OBP for RCP4.5. It shows an increase in ocean mass on the shallow shelf areas at the expense of the deep ocean regions. The strongest effect occurs along the North American east coast and off the coast of Alaska where the equivalent sea level rise exceeds 20 cm. In the shallow water regions along the coast in the Arctic, south East Asia, South America and Australia mass redistribution contributes with about 15-20 cm equivalent sea level rise. The increased OBP on the shelves is compensated by a decrease of OBP of around 5 cm equivalent sea surface height in the Atlantic Ocean and somewhat less in the Arctic Ocean, with rather uniform and minor changes in the Pacific Ocean. The drop in OBP is particularly evident in the western subtropical North Atlantic, showing a basin-scale drop up to about 10 cm. In addition, a net redistribution of water masses from the southern to the northern hemisphere takes place as most of the continental shelves are located in the northern hemisphere. For RCP4.5 the change in the mean sea surface height due to ocean mass redistribution is +1.5 cm for the northern and -1.1 cm for the southern hemisphere.

Self attraction and loading

Any change in the mass distribution within the ocean and/or solid earth will modify the Earth's gravitational field and will result in a further re-adjustment of the mass distribution. In addition, accumulation of mass on shallow shelf areas will increase the loading and lead to a deformation of the solid earth surface. The combination of these processes is referred to as self-attraction and loading (SAL) effect (Gordeev et al., 1977). Focus so far has been on the effect of melting land ice, i.e., the redistribution of mass from land to the oceans, and the subsequent adjustment of the sea surface to the perturbed gravity field (Tamisiea et al., 2003; Riva et al., 2010). Recently, Tamisiea et al. (2010) and Vinogradova et al. (2011) extended the SAL effect resulting from changes in hydrology, atmospheric loading and ocean dynamics, while Kuhlmann et al. (2011) explicitly incorporated SAL effects in a baroclinic ocean model.

Figure 2b shows the SAL fingerprint induced by the redistribution of ocean mass defined as the relative motion between the ocean surface and the solid earth (relative sea level, RSL). SAL effects cause a moderate sea level increase over the shelf areas of about one order of magnitude smaller than the forcing. Mean RSL over the shelves, defined as those areas with a bathymetry shallower than 700 m, is 1.0 cm for scenario RCP4.5 (0.8 and 1.5 cm for RCP2.6 and RCP8.5, respectively). The regional RSL increase can be up to 1–3 cm on high northern latitude shelves, depending on the scenario.

The SAL effect is negligible over the Pacific Ocean away from the East Asian shelves but reduces the sea level rise in the

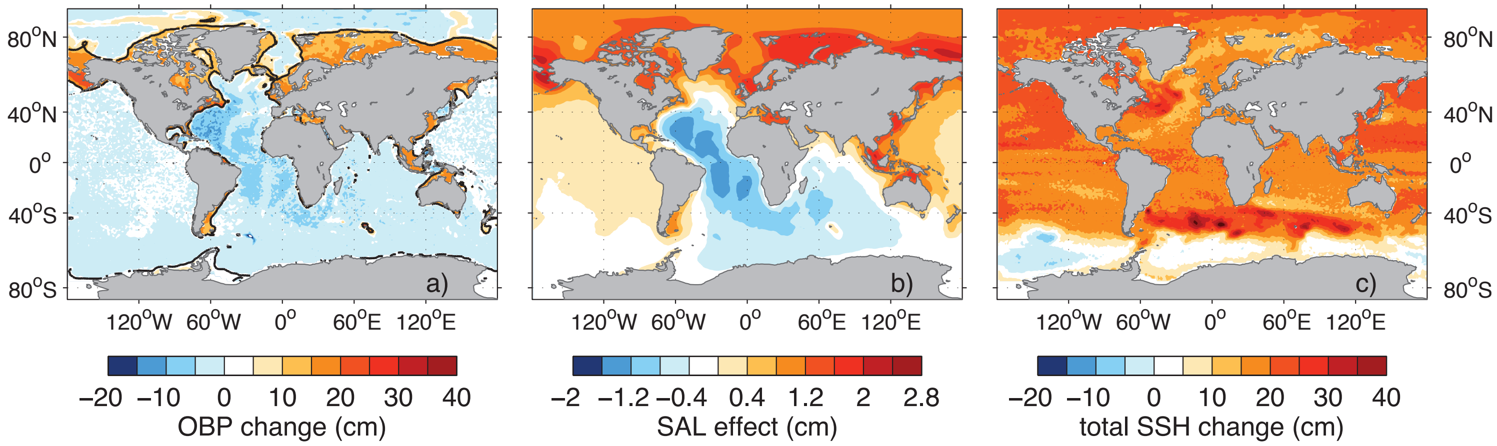

Figure 2. (a) Change in ocean bottom pressure from 2006–2015 to 2091–2100 in RCP4.5. Unit is mbar which roughly translates to cm. (b) 21st century change in relative sea level (in cm) due to self-attraction and loading effects induced by fields presented in Figure 2a. Note the different color scale. (c) Combined effect of changes in steric height (Figure 1c), ocean bottom pressure (Figure 2a) and SAL effects (Figure 2b).

entire interior Atlantic Ocean Atlantic south of 30°N by up to 10%. The SAL effect increases sea level rise by up to 15% in the Barents Sea and between 5 and 10% on the shallow shelves in high northern latitudes. This applies to RCP2.6 and RCP8.5 as well (Richter et al., 2013) and not only to RCP4.5.

Summary and Conclusion

Global steric sea level rise in NorESM1-M is 13, 18 and 28 cm for RCP2.6, RCP4.5 and RCP8.5, respectively. However, modeled sea level rise on the shallow shelf areas off most of the coastlines is mostly due to redistribution of water masses and only to a minor degree caused by local steric expansion. Figure 2c shows the change in sea surface height taking into account steric changes, sea water redistribution and SAL effects. The sharp cross-shelf gradients originating from steric changes only (Figure 1c) are eliminated. The remaining sea surface height gradients are related to localized (but still large-scale) heat and fresh water anomalies in the ocean, and to changes in ocean circulation.

The additional change in sea level due to SAL effects is relatively small compared to the combined regional changes due to steric changes and sea water redistribution. However, our results suggest that the average sea level rise on shallow shelf areas in the 21st century may be 5–6% larger (3–5% if the average is taken over coastal grid boxes only) than the globally averaged sea level rise due to thermal expansion. This is consistent with Gregory et al. (2012) who found a coastal sea level rise 3% stronger than the global mean.

Acknowledgments.

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Tides, Critical Latitude, and their Effects on the Amundsen Sea Ice Shelves

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Tidal effects on the flow in and out of ice shelf cavities and ice shelf melting were investigated using the Regional Ocean Modelling System (ROMS) for three ice shelves in the Amundsen Sea: Getz, Dotson, and Pine Island. Prior studies showed that flow into and under the ice shelf is primarily controlled by the topography of the sea floor and the ice shelf; however, tides played a significant role. Tides significantly increased mixing and the circulation under the Ronne-Filchner Ice Shelves and doubled ice shelf melting [Makinson et al. 2011] and generated mean currents up to 5 cm s^{-1} that equalled or exceeded the mean density-driven flow, doubled ice shelf melting, and modified its distribution under the Larsen C Ice Shelf [Mueller et al., 2012]. In the Amery Sea, tidal currents enhanced the melting and freezing rates with large fluctuations in heat content associated with the spring-neap cycle [Galton-Fenzi et al., 2012]. The goal here was to quantify tidal effects on the circulation and ice shelf melting in the Amundsen Seas through comparison of simulations performed both with and without tides.

The general circulation pattern of the mean flow had water entering the Dotson and eastern Getz ice shelf cavities on the eastern side and exiting on the western side (Figure 1a and 1b). For the Pine Island ice shelf cavity, mean flow entered on the northern side and exited on the southern side (Figure 1c).

In this region, diurnal tides are stronger than semidiurnal tides. However, even the maximum barotropic tidal velocities are small, particularly for Pine Island Bay, < 1.5 cm s^{-1}. The mean density driven flow of the ice cavity is 5-10 times stronger than the barotropic tidal velocities and 2-3 times the baroclinic tidal velocities.

The spatial mean melt rates over 30 days calculated for Pine Island Ice Shelf ranged from 16.9 to 20.2 m yr^{-1}, dependent on the forcing, tides and wind (Table 1). These melt rates are slightly lower than the observational estimate, 24 ± 4 m yr^{-1}, but agree within reason [Rignot 1998].

Even these weak tides in the simulation altered the mean inflow and outflow of the density-driven circulation. Circulation at the front of the Getz and Dotson ice shelves was stronger with tides than without (Figure 1), with the greatest changes deeper in the water column. Under the Getz Ice Shelf, the inflows increased as much as 5 cm s^{-1} (Table 1 and Figure 1a and 1f). Under Dotson, tides strengthened velocities by more than 10 cm s^{-1} below 400 m in places (Figure 1b and 1g) and inflow by 50% (Table 1). For Pine Island Ice Shelf, tides did not increase the inflow or the velocities in the cavity (Figure 1c and 1h). The differences in the mean inflows for Dotson and Getz exceeded both the barotropic and baroclinic tidal velocities. Thus, the changes in mean flow driven by the tides were not directly due the tidal velocities, but included density-driven flows resulting from changes in the amount of heat entering the cavity, different mixing environments, resonance effects, and other mechanisms. The ice shelf melting response was similar with tides having a significant impact on melt rates for Dotson and Getz Ice Shelf cavities with increases of 2.2 and 3.4 m yr^{-1}, respectively, but not for Pine Island (Table 1), with a decrease of 0.5 m yr^{-1}.

The different behaviours of these ice shelves was linked to the M_2 critical latitude (M_2 74° 28' S or 74.46° S), where the tidal frequency equals the inertial frequency. The fronts of Getz and Dotson Ice Shelves are equatorward of the M_2 critical latitude by 0.5-0.75° and Pine Island Ice Shelf is slightly poleward. Equatorward of critical latitude, Dotson, the circulation is baroclinic (Figure 1b) and poleward of critical latitude, Pine Island, it is barotropic (Figure 1c) , both of which are consistent with linear internal wave theory. To verify the critical latitude was a key factor, the domain for Pine Island Ice Shelf was shifted north by 1° so that the front of the ice shelf was equatorward of the M_2 critical latitude. At the shifted position, tides increased the velocities below 400 m, their baroclinicity (Figure 1d compared to 1c), and the melt rate by 2.7 m yr^{-1} (Table 1).

Defining effective critical latitude as the latitude where the total vorticity, planetary and relative, equals the inertial frequency, the effective critical latitude is offset from the critical latitude depending on the relative vorticity of the flow. Such shifts in critical latitude have been observed [Kunze and Toole 1997].

Ice Shelf	Melt Rate without Tides (m yr^{-1})	Melt Rate with Tides (m yr^{-1})	Inflow without tides (Sv)	Inflow with tides (Sv)
Getz	7.9	9.1	0.64	0.66
Dotson	6.5	9.9	0.13	0.21
Pine Island	16.9	16.4	0.09	0.08
Pine Island shifted 1° N	15.9	18.6	-	0.16
Pine Island with wind-driven gyre	-	20.2	-	0.10

Table 1. Melt rates and inflows for the Getz, Dotson, and Pine Island ice shelf cavities both without and with tides. Melt rates for two additional cases for the Pine Island Ice Shelf are given with the domain shifted 1° N and with a wind-driven gyre.

A wind-driven gyre with sufficient relative vorticity to shift the critical latitude ~1.0° S was observed during summer 2009 [Figure 13 in Tortell et al. 2012] and often exists in Pine Island Bay [Mankoff et al. 2012]. A simulation was performed with the Pine Island Ice Shelf at its real location with the wind conditions experienced during NBP0901. The resulting circulation into the ice shelf cavity is very similar to that of the shifted domain (Figure 1e compared to 1c). The melt rate with the wind-driven gyre is higher (Table 1). Thus, the wind-driven gyre effectively shifts the critical latitude 1º South, enabling tides to increase the circulation and melting.

The critical latitude also affects mixing, with mixing increasing near critical latitude due to increased shear in the flow. Taking diffusivities of temperature as determined by the model using the Mellor-Yamada 2.5 level turbulence closure scheme as indicative of mixing, mixing increased in the ice shelf cavity and in front of the ice shelf in Pine Island Bay both for the shifted domain (Figure 1i) and for the wind-driven gyre (Figure 1j) with significantly higher temperature diffusivities. With the wind-driven gyre, a beam of high diffusivity, typical for internal tides, emanates from the top of the ridge in the ice shelf cavity, reflecting higher mixing there (Figure 1j).

Tides have been shown to play a significant role in ice shelf melting and circulation under the ice shelf in strong tidal regimes, such as the Ross and Weddell Seas, through the mechanisms of tidal rectification and mixing [Makinson, et al., 2011; Mueller et al., 2012]. Here, tides are shown to play a significant role in even in weak tidal regimes for ice shelves near the effective critical latitude. Selected ice shelves along the Antarctic Peninsula, in the Weddell Sea, and Greenland, which are near the M_2 critical latitude, are likely to respond similarly. Tidal effects on the ice shelves in these areas near critical latitude result from internal tides, increased baroclinicity, resonance effects, increased mixing, and non-linear effects on the density-driven circulation, rather than tidal residual velocities. These effects can increase ice shelf melt rates by 25-50%.

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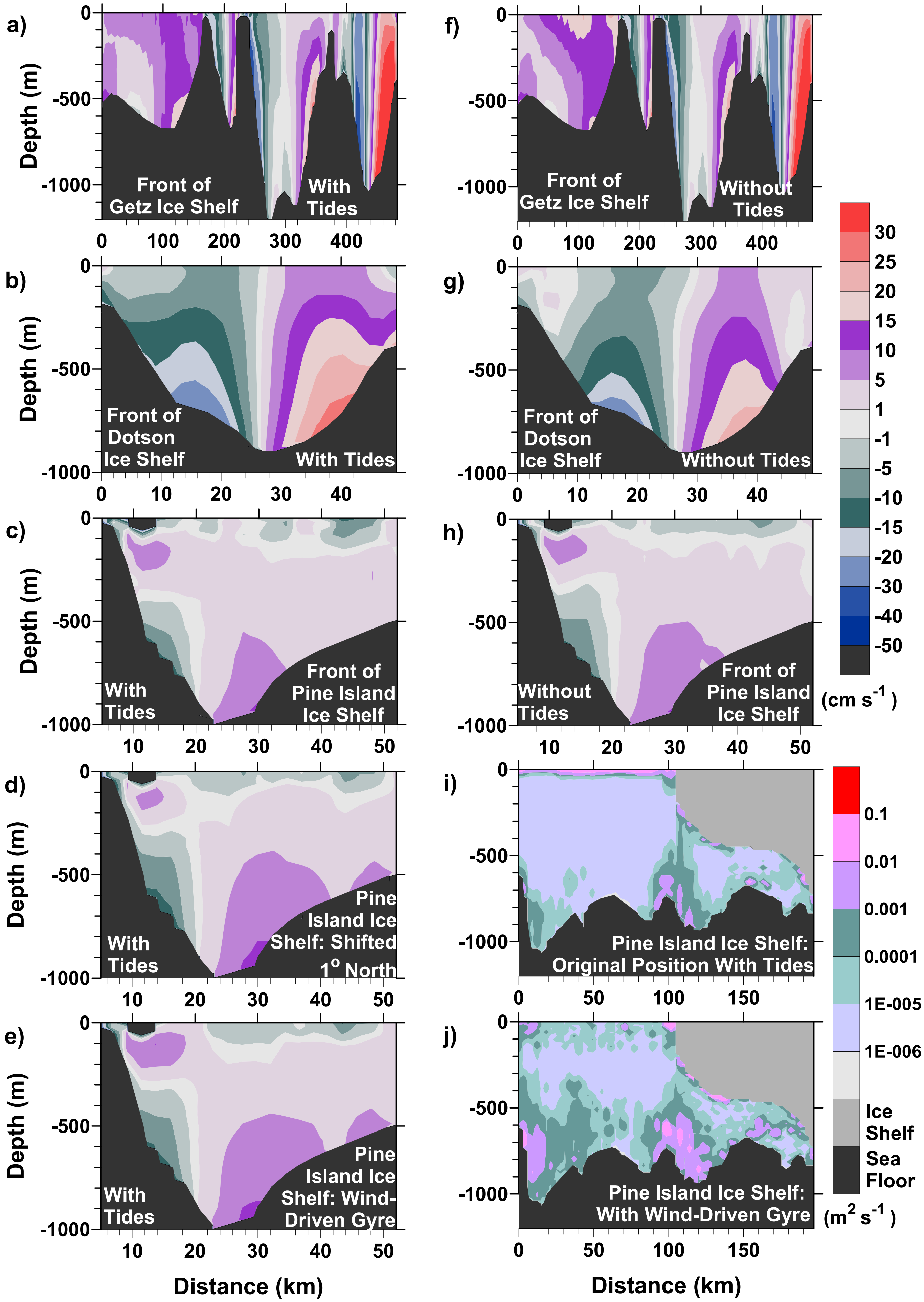

Figure 1: Mean velocities normal to the ice shelf front averaged for 30-days for the a) Getz, b) Dotson, and c) Pine Island ice shelves, d) Pine Island shifted 1° North, e) Pine Island with a wind-driven gyre with tides and f), g), h) for the Getz, Dotson, and Pine Island ice shelves without tides, respectively. Positive velocities (red and purple) indicate flow into the ice shelf cavity and negative velocities (blue and green) indicate flow out of the ice shelf cavity. Diffusivities of temperature in Pine Island Bay and under the ice shelf for simulations i) without and j) with the wind-driven gyre.

Report on the 11th Session of the CLIVAR Working Group on Ocean Model Development (WGOMD) Hobart, Australia, 21-23 February 2013

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The 11th Session of the CLIVAR Working Group on Ocean Model Development (WGOMD) was held in Hobart, Australia on 21-23 February 2013, hosted by S. Marsland, CSIRO.

The WGOMD panel meeting followed the Workshop on Sea-Level Rise, Ocean / Ice-Shelf Interaction, and Ice Sheets that was held on 18-20 February 2013, also in Hobart, Australia

(see the workshop report by Marsland et al., in this issue). The workshop was jointly organized by the WGOMD and the CLIVAR/CliC/SCAR Southern Ocean Region Implementation Panel (SOP).

WGOMD is coordinating the second phase of Coordinated Ocean-ice Reference Experiments (CORE-II) – hindcast simulations forced with interannually varying atmospheric data sets for the period 1948-2007 (Large and Yeager, 2009). The CORE-II Release Notes (Griffies et al., 2012) describe the datasets and protocol for running global ocean-ice climate models.

The CORE-II simulations provide a framework for i) evaluation, understanding, and improvement of the ocean components of earth system models; ii) investigation of mechanisms for seasonal, inter-annual, and decadal variability; iii) attribution of ocean-climate events to forced and natural variability; iv) evaluation of robustness of mechanisms across models; and v) bridging observations and modeling, by complementing ocean reanalysis from data assimilation approaches. The CORE-II hindcast simulations can also provide consistent ocean and sea-ice initial conditions for decadal prediction experiments.

The panel meeting focused almost entirely on presentations from CORE-II participants (available at http://www.clivar.org/organization/wgomd/activities/wgomd11) and discussions on the coordinated analysis efforts that are currently underway. Eighteen modeling groups are participating in the present effort. These include level, isopycnal, hybrid, mass, and sigma coordinate models, and an unstructured finite element ocean model; mostly with nominal 1° horizontal resolutions.

The following multi-model analyses are currently underway:

- Assessment of the North Atlantic solutions with a focus on the Atlantic meridional overturning circulation, Part I: Mean states; Part II: Variability (Danabasoglu, Yeager, & Bailey, et al.),
- Global and regional sea level (Griffies & Yin, et al.),
- Arctic Ocean and sea-ice (Gerdes, Wang, & Drange, et al.),
- The Antarctic Circumpolar Current and Southern Ocean overturning circulation with a focus on eddy compensation (Farneti & Downes, et al.),
- Evolution of Southern Ocean water masses and ventilation (Downes & Farneti, et al.),
- South Atlantic simulations (Treguier & Weiner, et al.),
- Ocean circulation in temperature and salinity space (Nurser & Zika, et al.)
- North Pacific and its variability (Y.-H. Tseng, et al.).

The WGOMD is actively promoting use and analysis of the CORE-II solutions. The CORE-II website (www.clivar.org/wgomd/core/core-2) has been developed to serve the community with information on how to participate in running the experiments and in their analysis. A CORE-II email list has been created to facilitate the exchange of news and information and to send data requests for coordinated analysis activities. A special issue of Ocean Modelling is being produced in late 2014, and the CORE-II website is being advertised as part of the special issue announcement.Other coordinated analysis efforts are encouraged from the CLIVAR community. The data (and potentially plotting/diagnostics tools) are freely available. NCAR has agreed to host and curate the dataset on its ESGF node and is currently testing the service with the NCAR datasets. Information will be available soon on how to access the centralized dataset via the CORE-II website. In the meantime, people can contact the individual modeling groups to obtain the data.

While WGOMD continues to focus on analyzing the CORE-II solutions until mid next year, some new activities are being planned as our near-term activities. A specific example is forcing ocean models with a partial coupling approach where an interactive atmosphere model is employed – thus allowing feedback – with some forcing components overwritten or controlled. Another example is high-resolution (eddy-permitting / eddy-resolving) ocean modeling as many groups are considering such high-resolution simulations as the computational resources become more available. There are many associated issues such as how to design scale-aware parameterizations. Based on our discussions, for the next 5-10 years, additional focus areas that we are considering include regional / coastal modeling; sea level and interactions with ice sheets; Atlantic meridional overturning circulation and role of ocean in decadal variability; and operational oceanography and data assimilation. Of course, WGOMD will continue to address model biases and improve model physics, also considering biogeochemistry and ecosystems, as part of its core objective. We note that our discussions occurred within the context of the new ocean – atmosphere CLIVAR, addressing key science questions.

WGOMD and SOP met jointly for a half-day to discuss the outcomes of the workshop and to promote coordinated research activities on ocean, ice shelf and ice sheet interactions (more details are given in Riley et al., this issue).

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Report of the 8th CLIVAR/ CliC/SCAR Southern Ocean Panel (SOP) meeting Hobart, Australia, 21 – 22 February 2013

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In February 2013 the 8th session of the CLIVAR/CliC/SCAR Southern Ocean Panel (SOP) was held over 2 days in Hobart, Australia. The science undertaken and workshops held since the last panel meeting were discussed. Alberto Naveria-Garabarto updated the panel on the Southern Ocean Observing System (SOOS) and Steve Rintoul reported on the SOOS under-ice observation workshop, held in Hobart in 2012. Lynne Tally provided an overview of the proposed C-SOBOM (Center for Southern Ocean Biogeochemical Observations and Modeling) programme. Jan Zika presented his work on the 'thermohaline streamfunction', a new technique to diagnose ocean circulation in temperature-salinity coordinates. The eddy physics of the Southern Ocean and its impacts on the Meridional Overturning Circulation (MOC) and the Antarctic Circumpolar Current were addressed by Andy Hogg, whilst Tas Van Ommen reported on the activates of the Antarctic 2K working group. Christian Jakob gave a presentation on cloud observations and modelling over the Southern Ocean region and Dave Thompson presented the latest findings and gaps in the knowledge about the mid-latitude Southern Hemisphere jet.

A joint session was held between the SOP and the Working Group on Ocean Model Development (WGOMD). Gokhan Danabasoglu opened this session with a talk about the CORE activity and ongoing model intercomparison projects. Riccardo Farneti gave a talk on the Southern Ocean CORE comparisons, whilst J.B. Sallee showed some of the latest results of the CMIP5 runs representing Southern Ocean processes. Stephanie Downes talked about the role of surface winds and buoyancy fluxes in varying the MOC under future climate scenarios. Simon Marsland presented a summary of the future Southern Ocean WGOMD activities. These included:

- Polynyas and climate change
- Studies of ice shelf water including in situ data for model comparison
- Improving parameterizations of modeled downslope overflow.
- Developing process studies in relation to CORE experiments

The overall future direction of the SOP was also discussed and the necessary actions needed to continue to progress the science were highlighted. Over the next 5 years some of the scientific questions that will guide the panel activities in parallel with the CLIVAR research opportunities and WCRP Grand Challenges, include:

- What is the future of Antarctic ice, including sea ice, ice shelves and land ice?
- What is the impact of acidification and how will the ocean store CO_2 in the future?
- How will the ongoing projected trends in the Southern Annular Mode impact on air-sea heat, moisture and carbon fluxes? What will be the impact on Southern Hemisphere regional climate?
- What is the future of the Antarctic continental margin?

In order for the community to make progress regarding these topics several white papers and review articles are presently under consideration. The SOP intends to maintain close interactions with SOOS, and to forge greater linkages with CliC. The meeting also identified the need to develop an improved knowledge of air-sea and ice-sea fluxes over the Southern Ocean; a lack of observations remains a problem for these parameters.

For further information on the talks and discussions that took place during the 8th session of the CLIVAR/CliC/SCAR SOP, please refer to the meeting report found online at www.clivar.org/publications/reports/reports_full.

Report on the 20th Annual Meeting of the CLIVAR Scientific Steering Group (SSG) Kiel, Germany 6-9 May 2013

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The CLIVAR Scientific Steering Group (SSG) met in Kiel, Germany, 6-9 May 2013 to discuss the accomplishments of the last year and future directions of the project for the coming year. The 4-day meeting was hosted by GEOMAR, the home institute of CLIVAR SSG co-chair Martin Visbeck. In total, 48 people participated over the four days of the meeting, with representatives from over 30 international academic institutions and scientific organizations. The meeting is the one opportunity in the CLIVAR calendar when the entire SSG and representatives from panels, working groups, national programmes, funders and other WCRP (World Climate Research Programme) core projects (CLiC, GEWEX and SPARC) all meet.

The meeting was opened with an overview of WCRP developments, in particular those related to the six Grand Challenges (Regional Climate Information; Sea-level Rise and Regional Impacts; Cryosphere in a Changing Climate; Clouds, Circulation and Climate Sensitivity; Changes in Water Availability; and Science Underpinning the Prediction and Attribution of Extreme Events). An important objective of the SSG meeting was to discuss how CLIVAR could best contribute to meeting these challenges. Representatives from the three other WCRP core projects, the Global Ocean Observing System (GOOS), as well the US CLIVAR program, provided updates on the status of their respective programmes. The SSG also heard reports on progress in planning two major WCRP regional conferences, the Africa Climate Conference that will take place in Arusha, Tanzania, 15-18 October 2013, and the Latin America and Caribbean Conference in Montevideo, Uruguay, 17-21 March 2014.

At last year's meeting in Mexico, SSG agreed that the organization of CLIVAR around "Capabilities" and "Research Opportunities" would provide a mechanism for the project to remain flexible and responsive to new ideas and challenges, and in particular those requiring cross-panel/project interactions, while at the same time ensuring that core CLIVAR science topics continue to be addressed.
Five "Research Opportunities" were identified highlighting areas that are primed for progress in the next 5-10 years, which would significantly benefit from enhanced international coordination, in addition to the core activities of the existing Panels and Working Groups. The Research Opportunities would be complementary to the core CLIVAR research activities, facilitated via the existing panels and working groups. Over the past year "Tiger Teams" composed of volunteer CLIVAR SSG and panel/working group/expert team members have worked with the wider community to identify key research priorities related to these topics. The Research Opportunities are:

- Intraseasonal, seasonal and interannual variability and predictability of monsoon systems;
- Decadal variability and predictability of ocean and climate variability;
- Trends, nonlinearities and extreme events;
- Marine biophysical interactions and dynamics of upwelling systems;
- Dynamics of regional sea level variability.

In Kiel, Tiger Team leads presented their reports (See: www.clivar.org/science/clivar-research-opportunities) and also discussed how the CLIVAR Research Opportunities would contribute to the WCRP Grand Challenges. In the spirit of a flexible framework, two new Research Opportunities were also proposed to the SSG:

- ENSO in a warmer world
- Planetary heat balance and ocean heat storage

The next steps, discussed at the SSG meeting, will see the development of each of the Research Opportunities into focused activities to be tractably implemented by the community. The Tiger Teams were charged to engage with the wider community to further refine their proposals. These will continue to be presented for input and discussion at various fora over the next 6-12 months, including the Fall AGU in December, the annual meeting of the AMS in January, and the Ocean Sciences meeting in Hawaii in February 2014. The implementation plans for the Research Opportunities will be presented and discussed at the pan-CLIVAR meeting 16-18 July 2014 and at the subsequent SSG meeting.

CLIVAR has 6 capabilities, which are carried out through the work of the panels and working groups. These capabilities are:

1 Improving the atmosphere and ocean component of Earth System Models.
2 Implementing innovative process and sustained ocean observations.
3 Facilitate free and open access to climate and ocean data, synthesis and information.
4 Support Regional and global networks of climate and ocean scientist.
5 Facilitate knowledge exchange and user feedback.
6 Support education, capacity building and outreach.

Representatives of the regional panels (AP, IOP, PP, SOP, AAMP, VAMOS) the global panels GSOP and CLIVAR/PAGES, together with WGOMD and ETCCDI, presented key accomplishments and described how their activities contribute to the new WCRP and CLIVAR foci. Some of the scientific achievements from the panels and working groups, highlighting the CLIVAR capabilities include:

- Asian Australian Monsoon Panel (AAMP) – supported the monsoon Intraseasonal Variability Hindcast Experiment (ISVHE) and has contributed to the development and continuing analysis of the numerical hindcast and forecast experiment. The ISVHE hindcast dataset can be used to determine predictability and prediction skill of the MJO and boreal summer ISO (BSISO), identify predictability sources in ISV time scale, investigate ISO teleconnections and impact on mid-latitude weather/climate and tropical cyclone, and construct optimal methods of the deterministic multi-model ensemble prediction and probabilistic multi-model prediction for ISVs.
- Variability of the American Monsoon System (VAMOS) – is currently heavily involved with the organisation of the Latin American and Caribbean WCRP conference, (to be held in March 2014) including development of the steering committee and scoping of the conference plan.
- Working Group on Ocean Model Development (WGOMD) – The Coordinated Ocean-ice Reference Experiment (CORE) is designed for global ocean-ice models to be run for long-term climate studies and as a framework where the experimental design is flexible and subject to refinement as the community gains experience. The second phase CORE-II, using inter-annually varying atmospheric forcing over the 60-year period from 1948 to 2007 has disproved the hypothesis that models run with the same forcing generate the same response. Papers on the Atlantic MOC (mean state and variability) and on global and regional sea level rise are in press.
- Expert Team on Climate Change Detection Indices (ETCCDI) the ClimDEX Project will produce global gridded indices of temperature and precipitation extremes. HadEX2, an updated HadEX indices product, has been developed including results from ETCCDI regional workshops. The CMIP5 model simulations have been analysed with the ETCCDI extremes indices.
- Atlantic Implementation Panel (AIP) – with the end of the CLIVAR-TACE programme the AIP is currently developing a new direction for tropical Atlantic research, focusing on better understanding the role of the eastern tropical upwelling systems in tropical Atlantic variability.
- Indian Ocean Panel (IOP) – has developed an implementation plan for, and is coordinating the implementation and maintenance of the Indian Ocean Observing System (IndOOS). The IOP is also involved with making cross-institutional IndOOS data accessible through a data portal site.
- Global Synthesis and Observations Panel (GSOP) - the evaluation of the current generation of ocean synthesis/reanalysis products, promoting their application to study ocean circulation and its relation to climate. The evaluation has led to improved understanding about the consistency and fidelity of many aspects of ocean synthesis products (e.g., heat content, meridional overturning and related heat transport, major ocean current transports, etc.).
- Pacific Panel (PP) – Is currently addressing the future of the TAO array and how best to develop a sustainable ocean observing system in the tropical Pacific given the scientific and societal needs, and the new knowledge and technology available.

- CLIVAR/PAGES – has been involved with the formation of the Ocean2K network (the 9th group in the PAGES 2K network). Motivating this project is the interest in placing observed historical marine conditions into the context of climatic variation over the past 2,000 years.
- Southern Ocean Panel (SOP) – was involved with the Southern Ocean FINEstructure (SOFINE) project making the first full-depth microstructure measurements of turbulence in the Antarctic Circumpolar Current and, for the first time, a direct study of the relationship between the internal wave field and turbulent dissipation and mixing in the Southern Ocean interior.

For more in depth discussions of the panel and working group activities please refer to the individual reports available at www.clivar.org/about/scientific-steering-group/activities/SSG20.

Discussions followed on how best to organize CLIVAR to allow both the continuation of the existing science under the core panels and development of the new, time limited Research Opportunities. Discussions were animated with contrasting opinions and perspectives voiced. The future designation of a global Monsoons Panel, following a gradual transition from the current regional monsoon panels, was discussed and later agreed by the WCRP Joint Scientific Committee (JSC) at its session that took place during the last week of May. The JSC also endorsed the new CLIVAR strategy and agreed to the name change: CLIVAR – Oceans and Climate: Variability, Predictability and Change. With the overall goal to: To improve understanding and prediction of ocean-atmosphere interactions and their influence on climate variability and change, to the benefit of society and the environment.

CLIVAR has the lead on the WCRP "Sea-level Rise and Regional Impacts" Challenge and will develop a single implementation plan for both the CLIVAR Research Opportunities and the WCRP effort. GEWEX and CLIVAR have appointed a joint task team to take forward the WCRP Grand Challenge on Extremes to which the CLIVAR Research Opportunity on Extremes will contribute. CLIVAR Research Opportunities on monsoons and decadal predictability will be integral components of the WCRP Regional Climate Grand Challenge.

Presentations on CLIVAR and WCRP communications, outreach, including the development of the Early Career Scientists (ECS) network, and capacity building were also made. Post presentation discussions focused on the future of the ECS network and use of social media to promote CLIVAR and WCRP science. The discussions provided the impetus for the SSG to propose a new CLIVAR working group focusing on communication, knowledge exchange and outreach.
Looking to the future, the pan-CLIVAR meeting, co-located with the pan-GEWEX meeting in The Hague, Netherlands, in July 2014 will provide a unique opportunity for all CLIVAR panels and working groups to meet together under one roof for the first time and also promote further collaborative work between CLIVAR and GEWEX. Whether the SSG meets again later in 2014, in addition to this venue, is yet to be decided. Nevertheless, the future of CLIVAR and the science undertaken looks set to progress in new and exciting directions over the next few years.

The Climate Historical Forecast Project Database: Seasonal Hindcasts for Scientific Research

The Working Group on Seasonal to Interannual Prediction (WGSIP), in collaboration with the Centro de Investigaciones del Mar y la Atmósfera (CIMA) announce the availability of the CHFP dataset of seasonal hindcasts from leading seasonal forecast centres worldwide for research use.

The CHFP database consists of data from retrospective predictions of the seasonal climate from year to year across recent decades and is available from the website below.

The database currently contains data from 13 systems and will continue to grow over coming years to serve as a quantitative record of progress in global seasonal forecasting capability.

We encourage the research community to take advantage of this new and growing resource in their studies of the seasonal predictability of global climate in parallel to the CMIP database for longer term climate studies.

See the website for access and acknowledgement details:

CHFP: http://chfps.cima.fcen.uba.ar/

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C I M A CONICET U B A

WCRP World Climate Research Programme

Erratum

Correction for the Exchanges Issue 61 Editorial (R. Barry): The MJO Task Force is not part of DYNAMO. DYNAMO is the US portion of the DYNAMO/CINDY2011 field campaign that was centred on the Indian Ocean during late 2011 - early 2012, and subsequent modelling activities focussing on this period. The PI of DYNAMO is Chidong Zhang. The MJO-TF and DYNAMO researchers interact, but neither is "part" of the other. In particular, the MJO-TF spans more than just the US and is not focussed on any particular period. CINDY2011/DYNAMO was separately endorsed by CLIVAR.

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