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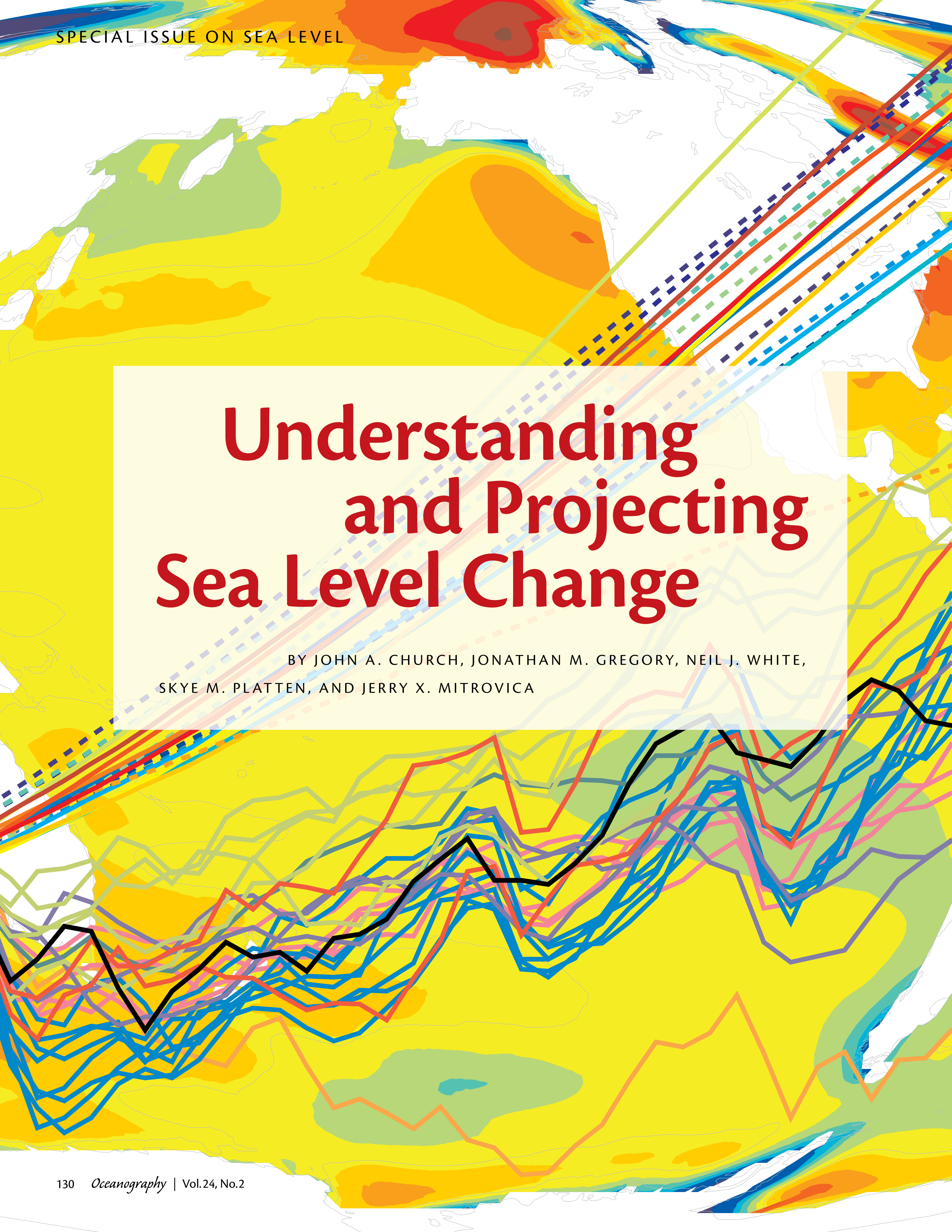
Oceanography



Understanding and Projecting Sea Level Change

BY JOHN A. CHURCH, JONATHAN M. GREGORY, NEIL J. WHITE, SKYE M. PLATTEN, AND JERRY X. MITROVICA

ABSTRACT. There is intense scientific and public interest in the Intergovernmental Panel on Climate Change (IPCC) projections of sea level for the twenty-first century and beyond. The Fourth Assessment Report (AR4) projections, obtained by applying standard methods to the results of the World Climate Research Programme Coupled Model Experiment, includes estimates of ocean thermal expansion, the melting of glaciers and ice caps (G&ICs), increased melting of the Greenland Ice Sheet, and increased precipitation over Greenland and Antarctica, partially offsetting other contributions. The AR4 recognized the potential for a rapid dynamic ice sheet response but robust methods for quantifying it were not available. Illustrative scenarios suggested additional sea level rise on the order of 10 to 20 cm or more, giving a wide range in the global averaged projections of about 20 to 80 cm by 2100. Currently, sea level is rising at a rate near the upper end of these projections. Since publication of the AR4 in 2007, biases in historical ocean temperature observations have been identified and significantly reduced, resulting in improved estimates of ocean thermal expansion. Models that include all climate forcings are in good agreement with these improved observations and indicate the importance of stratospheric aerosol loadings from volcanic eruptions. Estimates of the volumes of G&ICs and their contributions to sea level rise have improved. Results from recent (but possibly incomplete) efforts to develop improved ice sheet models should be available for the 2013 IPCC projections. Improved understanding of sea level rise is paving the way for using observations to constrain projections. Understanding of the regional variations in sea level change as a result of changes in ocean properties, wind-stress patterns, and heat and freshwater inputs into the ocean is improving. Recently, estimates of sea level changes resulting from changes in Earth's gravitational field and the solid Earth response to changes in surface loading have been included in regional projections. While potentially valuable, semi-empirical models have important limitations, and their projections should be treated with caution.

INTRODUCTION

Sea level change is a high-profile aspect of climate change and, as the paper by Nicholls (2011, in this issue) demonstrates, there are potentially significant impacts for our modern coastal society. As a result, there is huge demand for improved projections of sea level change, particularly at the local and regional level. Given this demand, it is very easy for assessments of projections of sea level change for the twenty-first century and beyond to be misinterpreted. Consequently, care is needed to ensure that these projections and the related uncertainties are accurately described and based on sound science, and that the uncertainties are reduced to the extent possible.

Sea level change is very much an interdisciplinary science. In addition to observations of sea level on multiple time scales, it is essential to consider changes in the ocean, cryosphere, solid Earth, and terrestrial storage of water, as covered in other papers in this issue. To formulate projections that cover the full range of possibilities, it is also necessary to consider future greenhouse gas emissions and concentrations, changes in the aerosol concentrations of the troposphere (from natural and anthropogenic emissions) and the stratosphere (from volcanic eruptions), the sensitivity of the climate system, and the resultant atmospheric changes.

Reliable projections of sea level change depend critically on improved understanding of the full range of underpinning issues, the rigorous testing of models of all aspects of the climate system contributing to sea level change, and the complexities of combining these terms. Projections will be most useful if they can be presented in probabilistic terms. However, the inability to fully understand the causes of sea level change has limited the ability to make this kind of presentation in previous assessments by the Intergovernmental Panel on Climate Change (IPCC). It is important to recognize that the IPCC reports are neither original research by the lead authors nor simply reviews of the existing scientific literature. They are critical assessments of what the scientific community does and does not understand at the time of writing. For IPCC Working Group I (WG1), the assessment is based on results published in the peer-reviewed literature and the application of established techniques. The sea level projections of the IPCC WG1 Fourth Assessment Report (AR4, completed in 2007) were obtained by applying methods available in the preceding year to the latest results from climate model simulations organized through the World Climate Research Programme (WCRP) Coupled Model Intercomparison Projects (CMIP; http://cmip-pcmdi.llnl.gov).

Here, we give an overview of the IPCC

AR4 projections and the limitations of these projections. We then discuss progress since the AR4 and prospects for improved global and regional projections. We also offer some cautionary comments on the use of semi-empirical models without adequate understanding of their potential limitations.

THE IPCC AR4 PROJECTIONS OF GLOBAL AVERAGED SEA LEVEL RISE

Projections for global averaged sea level rise for the IPCC AR4 were based on global climate model simulations completed as part of an internationally organized set of simulations (called CMIP-3; http://cmip-pcmdi.llnl.gov). They were completed for prescribed changes in greenhouse gas concentrations and other climatic forcings for the twentieth century and, following the IPCC Special Report on Emission Scenarios (SRES, http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission), for the twenty-first century. The results given here are for the years 2100 and 2090, compared to the 1980 to 1999 averages.

Ocean thermosteric sea level rise was estimated directly from global coupled atmosphere-ocean general circulation models (usually called AOGCMs). Many leading climate groups around the world develop and run these models, which simulate a wide range of physical processes. For each model simulation, the initial conditions were obtained from a long control simulation with steady climate forcing representative of pre-industrial conditions. Many historical simulations commenced in 1850, branching from the control simulation. Any low-frequency drift in these control runs was subtracted from the transient runs to focus on the impact of the time variable radiative forcings. The historical simulations included observed greenhouse gases and estimates of aerosols, but not all models used identical historical forcings. For example, some models included stratospheric aerosol loading following major volcanic eruptions while other models did not. (See http://cmip-pcmdi.llnl.gov/ for a more complete description.) As not all SRES scenarios were simulated with AOGCMs, a simple climate model (Wigley and Raper, 2001) was used to estimate a time-dependent ratio between scenarios (Meehl et al., 2007). Model-projected thermosteric sea level rise for the six marker SRES scenarios ranged from 11–44 cm. Figure 10.31 of Meehl et al. (2007) gives the spread of thermosteric expansion across the models for three scenarios.

The contribution from loss of mass by glaciers and ice caps (G&ICs; not including the major ice sheets of Greenland and Antarctica) in the IPCC Third and Fourth Assessment Reports (TAR [Church et al., 2001] and the AR4 [Meehl et al., 2007], respectively) was calculated using temperature projections with respect to a climate in which glaciers were estimated to be in a steady state (somewhat cooler than the late nineteenth century), an estimate of the present volume of G&ICs, and the global glacier surface mass balance sensitivity to temperature (i.e., the increase in the rate of loss of mass of G&ICs per degree rise in global temperature). The calculations did not include changes in precipitation because, on a global scale, precipitation changes have been shown to be less important than temperature variation for changes in G&IC volumes (see Meehl et al., 2007, for details). In TAR, the surface-specific mass balance sensitivities were taken from the studies of Zuo and Oerlemans (1997) and combined with surface temperature projections following the approach of Gregory and Oerlemans (1998). In the AR4, it was acknowledged that these surface mass balance sensitivities were too small to explain the observed glacier melting. Instead, a global average mass balance sensitivity was calculated by regressing the total mass balance changes summarized by Kaser et al. (2006) against observed global averaged surface temperatures, and the difference between them and model-based estimates was

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taken as an indication of the uncertainty in this quantity. There is now independent evidence that the Zuo and Oerlemans (1997) specific mass balance sensitivities were underestimated (LeClercq et al., in press). The calculated G&IC contribution across the six marker SRES scenarios ranged from 7–18 cm.

In a warmer climate, surface melting and snowfall are both predicted to increase in Greenland, with the former increasing more rapidly so there is an increasing net mass loss to the ocean. In Antarctica, there is no significant surface melting, and increased snowfall is projected, partially offsetting contributions to sea level rise from loss of mass in the West Antarctic Ice Sheet and other components of the climate system. In the AR4, these effects were estimated using the ice sheet mass balance sensitivities reported in Gregory and Huybrechts (2006). Further mass loss from the ice sheets could occur if they discharged more ice into the ocean as icebergs. Indeed, recent observations have identified an acceleration of the outlet glaciers in some regions of both the Greenland and Antarctic ice sheets (see, for example, Rignot et al., 2011). However, there is incomplete understanding of the reasons for these changes, which depend on processes not simulated in the ice sheet models available for the AR4. Hence, there was an inadequate basis for modeling any future acceleration. In recognition of this deficiency, a constant contribution of 0.32 mm yr^{-1}, corresponding to an additional 3.5 cm by 2100, was included in the projections up to 2100, based on observational estimates of recent changes and assuming that no further acceleration would take place. The net calculated contribution for the Greenland and Antarctic ice sheets across the six marker SRES scenarios ranged from 1 cm to 14 cm and –15 cm to –2 cm, respectively.

We combine all the contributions to give projections of global averaged sea level rise in 2100 for the SRES scenarios and for the range of AOGCMs available (Figure 1). The projected global averaged sea level rise for the SRES scenarios range from 19 cm (the bottom of the B1 Scenario) to 63 cm (the top of the A1FI scenario). These values are marginally higher than the often-quoted range given in the AR4 projections of 18 cm to 59 cm because they are for 2100 (rather than the average of 2090–2099 as in the AR4) and because the projected rate of sea level rise is large by the end of the century. Note that there was no allowance in these AR4 projections for the (likely small) changes in terrestrial storage.

To illustrate the effect of possible dynamic changes in the ice sheets (termed "rapid ice" contributions), Meehl et al. (2007) considered two alternative assumptions. In the first, the recent changes were assumed to be a transient adjustment process not necessarily related to climate change, and modeled as decaying to zero over coming decades. In the second, the recent ice sheet changes were assumed to be directly related to global climate change, implying they would increase with further warming. As there were no available models to estimate this ongoing response, Meehl et al. (2007) assumed linear scaling with global average temperatures. These two assumptions change the global average sea level projections for the highest greenhouse gas scenario considered (A1FI) from about –1 cm in the first scenario to about +17 cm in the second scenario, giving a total range in 2100 of 18–80 cm (Figure 1a). However, it is important to recognize that there is no firm theoretical or observational basis for linear (or any other) scaling and that larger sea level rise may be possible. The AR4 explicitly states that its projections for sea level rise do not give a best estimate or an upper bound. Note that since publication of the AR4, Pfeffer et al. (2008) have argued that a rise in excess of 2 m is "physically untenable," and that a rise of 0.8 m is more plausible.

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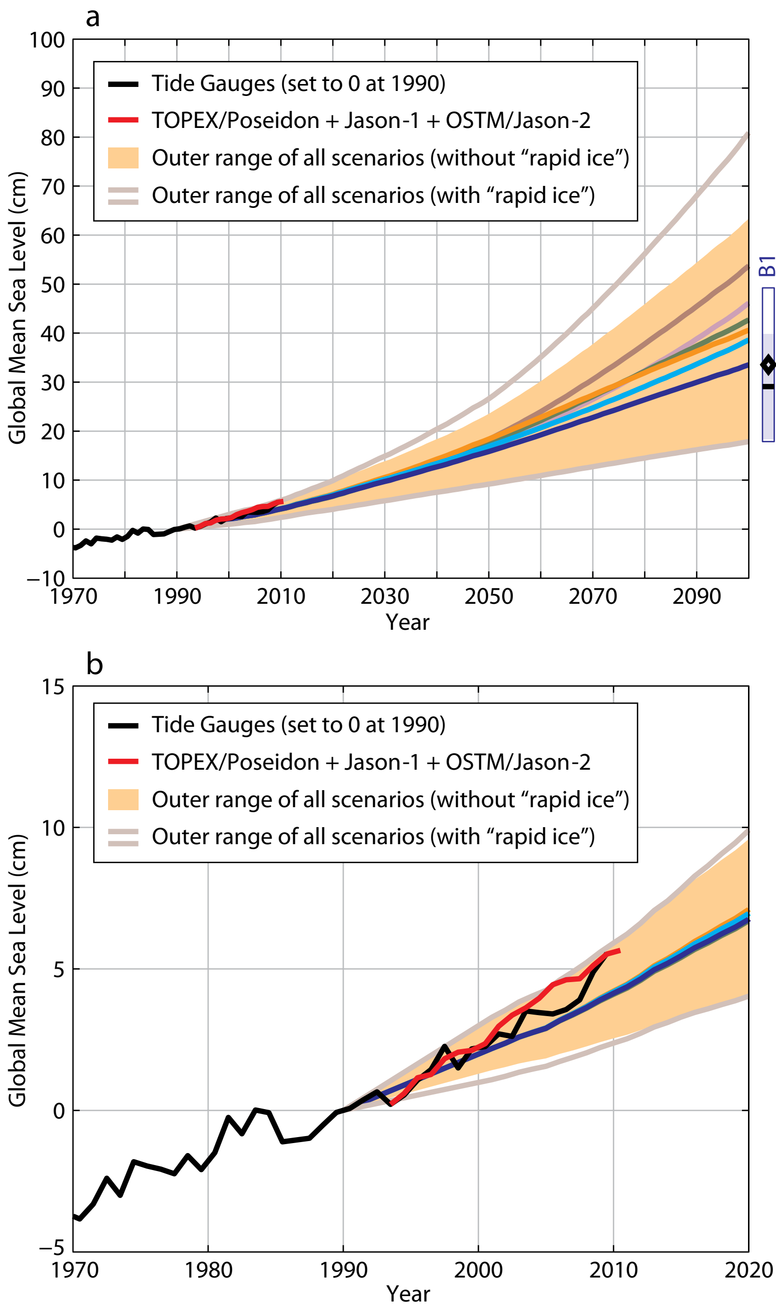

Figure 1. Global averaged projections of sea level rise in the IPCC Special Report on Emission Scenarios (SRES) to 2100 (a) and 2020 (b) with respect to 1990. The shaded region/outer light lines show the full range of projections, not including/including any rapid ice component. The continuous colored lines from 1990 to 2100 indicate the central value of the projections, including the rapid ice contribution. The bars at right show the range of projections for 2100 for the various SRES scenarios. The horizontal lines/diamonds in the bars are the central values without and with the rapid ice sheet contribution. The observational estimates of global averaged sea level based on tide-gauge measurements and satellite altimeter data are shown in black and red, respectively. The tide-gauge data are set to zero at the start of the projections in 1990, and the altimeter data are set equal to the tide-gauge data at the start of the record in 1993. The projections are based on the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4).

LIMITATIONS OF CURRENT PROJECTIONS OF GLOBAL AVERAGED SEA LEVEL RISE

Robust projections of sea level rise depend critically on understanding past sea level changes and being able to adequately represent them in model simulations. In the AR4, the observed global mean sea level rise for the period 1993 to 2003 was satisfactorily explained, that is, within formal uncertainty limits, by the sum of the contributions (using observations and models). However, the sum of contributions was biased low with respect to the observed total (Hegerl et al., 2007). Over the twentieth century (TAR) and since 1961 (AR4), the sum of the observed components and the modeled components was less than estimates of the observed sea level rise (Church et al., 2001; Hegerl et al., 2007). The inability to satisfactorily explain observed sea level rise over decades has been a significant limitation in all of the IPCC assessments to date and a barrier to narrowing projections of observed sea level rise.

Consistent with the above results, Rahmstorf et al. (2007) showed that observed sea level rise from tide gauges (1990 to 2001) and from satellite altimeter data (1993 to 2006) was reaching the upper limits of TAR projections. We have repeated the comparison of observed and projected rise (Figure 1b) with an improved sea level reconstruction (Church and White, 2011) and a longer altimeter time series along with the AR4 projections, and set the altimeter data to have the observed sea level equal to zero at the start of the projections and the start of the altimeter data in order to have the same value as the reconstructed sea level in 1993. Note that the fall in the reconstructed sea level from 1991 to 1993 is consistent with the volcanic eruption of Mount Pinatubo in 1991 and the subsequent cooling of the ocean (see below). By the end of the observational time series, both the reconstructed and altimeter sea levels are close to the top of the projections.

PROGRESS SINCE THE AR4 AND PROSPECTS FOR THE FUTURE

Since the AR4, revised observational estimates of changes in ocean heat content and thermosteric sea level rise, glacier melting, and ice sheet contributions, as well as additional modeling studies, have resulted in an improved explanation of the observed rise since 1970 and for the altimeter period since 1993. New and improved data sets have resulted from major international climate research programs organized by WCRP and the Global Climate Observing System, the continuing series of satellite altimeter missions (particularly TOPEX/Poseidon, Jason-1, and Ocean Surface Topography Mission/Jason-2), measurements of changing ocean and ice sheet mass using spaceborne gravity data from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004), and much-improved ocean observations from the Argo project.

Here, we present a brief summary of some of the major opportunities for improving projections of sea level rise.

Steric Sea Level Rise

There has been significant progress over the last half decade in understanding global ocean heat uptake and thermosteric sea level rise. Note that halosteric contributions are important for regional distribution of sea level rise but not for global averaged rise. Gouretski and Koltermann (2007) demonstrated that there were significant time-dependent biases in expendable bathythermograph (XBT) ocean temperature observations. Because XBT observations form the largest part of the historical data base, these biases and large gaps in historical data led to biases in trends of ocean heat content and thermosteric sea level and unrealistically large decadal variability (Gregory et al., 2004; AchutaRao et al., 2007), substantially exceeding the variability simulated by climate models. Although inaccurate fall-rate calculations for XBT probes resulted in errors in the recorded depths of observations, resulting biases have been approximately corrected (Wijffels et al., 2008; Ishii and Kimoto, 2009), yielding improved estimates of the heat content of the upper 700 m of the ocean. Consequently, it is now known that observational estimates of thermal expansion used in the AR4 were biased high in the 1970s and 1990s (Domingues et al., 2008; Wijffels et al., 2008; Ishii and Kimoto, 2009). The new estimates (Domingues et al., 2008; Ishii and Kimoto, 2009; Levitus et al., 2009) all have smaller interannual variability, a substantial part of which appears to be directly related to major volcanic eruptions (Figure 2).

Compared with the improved upper-ocean observational database, AOGCM simulations that only included anthropogenic forcing (and not the natural forcings, primarily stratospheric aerosols from explosive volcanic eruptions) show significantly larger trends as well as less variability (Domingues et al., 2008; Figure 2). In contrast, the variability in AOGCMs that do include these natural climate forcings is similar to observed ocean variability. AOGCM simulations with natural forcings also suggest that thermosteric sea level would have fallen by several millimeters following the eruption of Mt. Pinatubo in 1991 and that the ocean recovery from this cooling could add about 0.5 mm yr^{-1} to the rate of thermosteric sea level rise over about a decade from 1993, coincident with the first decade of high-quality satellite altimeter observations (Church et al., 2005; Gregory et al., 2006).

Analysis of the observational database leading to better understanding of the instrumental biases and new approaches to analyzing the sparse historical database are continuing (e.g., Palmer et al., 2007; Lyman et al., 2010). Recent estimates of significant deep-ocean warming and thermosteric sea level rise (e.g., see Purkey and Johnson, 2010) are particularly important. However, rigorous comparisons of climate model simulations with these deep-ocean changes are yet to be completed and should be pursued. The Argo program (Gould et al., 2004; Leuliette and Willis, 2011, in this issue) with its much-improved quality and coverage of temperature and salinity in the upper 2,000 m is providing a step change in our ability to observe the ocean. This time series is still short (global coverage from about 2004–2005) and additional ocean observations from 2,000 m to the ocean floor, in marginal seas, and under ice are required. As the Argo time series lengthens and can be confidently appended to earlier observational time series, ocean heat content and steric sea level rise estimates will become an increasingly powerful test of climate models.

The ocean varies on long time scales and thus ocean thermosteric sea level rise will continue for centuries, even after greenhouse gas levels are stabilized in the atmosphere, and thus the change is very likely irreversible on any practical human time scale (Solomon et al., 2009). The amount of eventual global mean sea level rise is roughly proportional to the eventual global average temperature rise, on the order of 20–60 cm per degree Centigrade of global averaged warming (Meehl et al., 2007).

Glaciers and Ice Caps

Glaciers and ice caps contain only a small fraction of the volume of water in the ice sheets of Greenland and Antarctica. However, they are generally at lower latitude with a surface temperature closer to 0°C. As a result, they are more vulnerable to global warming. It is not feasible to individually model some 200,000 glaciers and ice caps, the vast majority of which have not been studied in detail. Instead, estimates of historical contributions and twenty-first century projections depend on observations of surface mass balance from the small number of well-studied glaciers, and the extension of these estimates to other glaciers within and across regions.

The AR4 relied on the synthesis of Kaser et al. (2006) for estimates of G&IC contributions to sea level rise since 1960. Since publication of the AR4, updated G&IC inventories (Radić and Hock, 2010) have resulted in a larger volume estimate and allowed explicit inclusion of the G&ICs of Greenland and Antarctica in projections; the latter was accomplished in the AR4 by using a constant scaling factor. The data set of G&IC mass balance was expanded by using "geodetic" observations of glacier volume change in addition to surface mass balance observations (Cogley, 2009). Most recently, LeClercq et al. (in press) used glacier length observations together with the surface mass balance

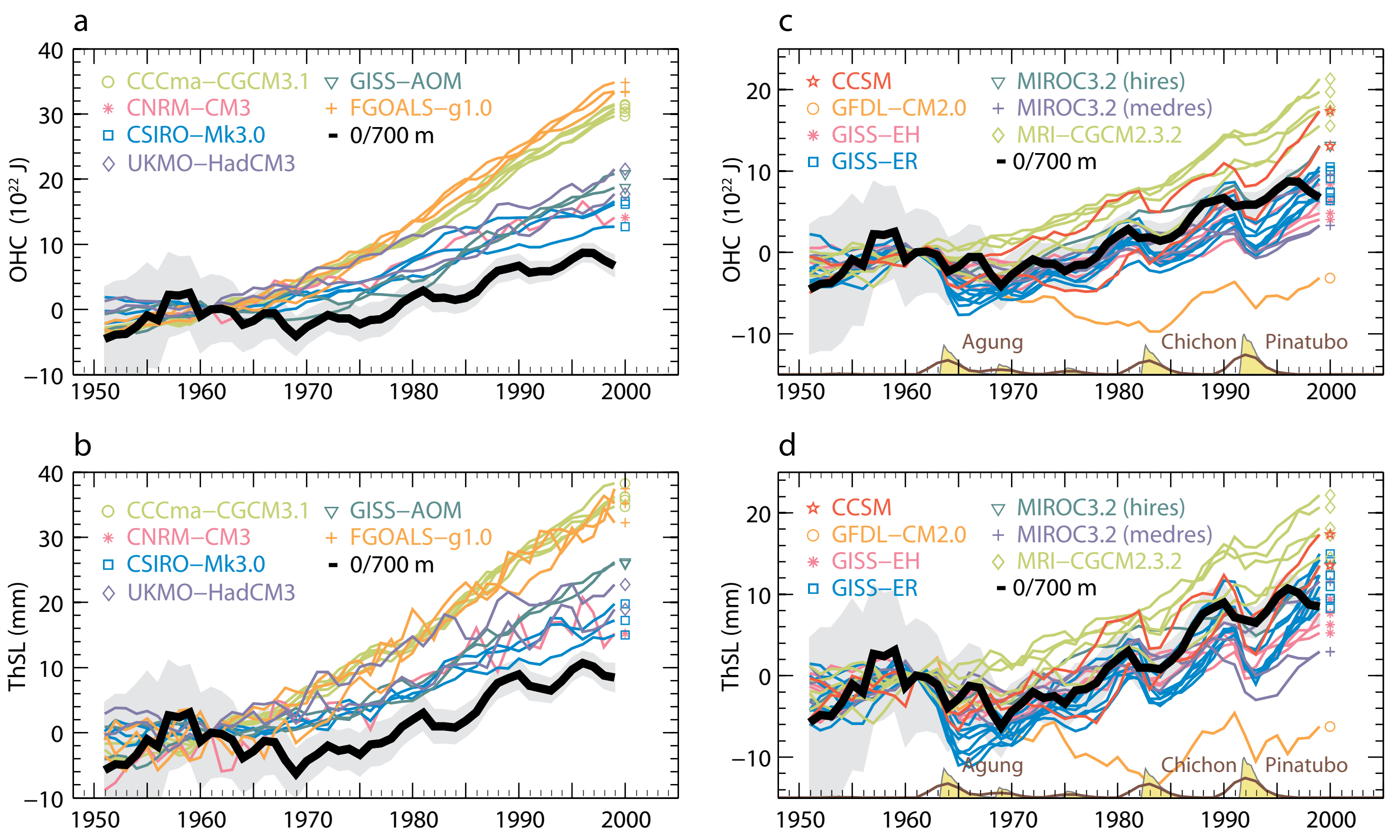

Figure 2. Comparison of observed and simulated ocean heat content (OHC; a and c) and thermosteric sea level (ThSL; b and d) estimates for the upper 700 m. (a and b) Models without volcanic forcing and (c and d) with volcanic forcing. The observations are running three-year averages and the model results are yearly averages. All models include greenhouse gas and tropospheric aerosol forcings. The stratospheric aerosol loading of major volcanic eruptions is shown at the bottom of (c) and (d). The brown curve is a three-year running average of these values included for comparison with the smoothed observations. The grey shading indicates one standard deviation error estimate for the observed time series, and all time series are relative to 1961. *From Domingues et al. (2008)*

observations compiled by Cogley (2009) to estimate G&IC contributions since 1800. Repeating the AR4 calculations for the A1B scenario based on the increased volume estimate of Radić and Hock (2010) and the mass balance estimates of Cogley results in a larger G&IC contribution of between 15 and 19 cm for most of the models (excluding two outliers) by 2100 compared to 1990 (Figure 3), larger than the AR4 projections of 7–18 cm.

As G&ICs lose mass, their surface area decreases and they retreat to higher altitudes, slowing the melt rate for the same climatic conditions. In TAR and the AR4, these area reductions are included in the G&IC projections by using area-volume scaling (Van de Wal and Wild, 2001). However, this method neglects the fact that the area reduction is greater at lower altitude, where the glacier is most vulnerable to increased melting. Recently, Radić and Hock (2011) improved on the techniques used in previous IPCC assessments by allowing for this effect, through consideration of hypsometry (the distribution of area with altitude). This added input allows G&ICs to come to a new equilibrium in a warmer climate. For the A1B scenario, they found the projected sea level contribution from G&ICs from 2000 to 2100 to be 0.12 ± 0.04 m, similar to the IPCC AR4 estimates but less than the estimates given above.

In the longer term, G&ICs can make only a limited contribution to sea level rise, and it would likely be restricted to those at higher altitudes and latitudes.

Ice Sheets

Recent investigations have explored the uncertainties in the models used to make projections of change in Laurentide Ice Sheet surface mass balance (Graversen et al., 2010; Bougamont et al., 2007). In most previous work, including the AR4, such projections have used empirically calibrated schemes for melting as a function of temperature change. More recent work on the ice sheet regions employs climate models at high resolution that incorporate detailed physical models of the surface energy balance, melting and runoff, and snow accumulation, both for Greenland (Fettweis et al., 2011) and Antarctica (Krinner et al., 2007).

Stimulated in part by the AR4 assessment that the state of scientific understanding at that time was not sufficient to support projections of the potentially large changes in ice sheet dynamics, much attention has been directed in recent years to developing improved models of ice sheet dynamics. Some first results are now available (Joughin et al., 2010) and more are expected as an outcome of two large ongoing activities, the SeaRISE project supported by NASA, and the EU-funded ice2sea project.

It is thought likely that the recent accelerations in both ice sheets have been brought about by the incursion of relatively warmer ocean water underneath ice shelves (e.g., Holland et al., 2008; Nick et al., 2009), though it is as yet unclear whether these warmings are natural fluctuations or connected with anthropogenic climate change. The warming leads to (and any future warming is also likely to lead to further) basal melting and thinning of the ice shelf, reducing the "buttressing" effect of the ice shelf on the ice sheet. Consequently, the ice flow on land accelerates toward the ocean as observed in the Antarctic Peninsula (Rignot et al., 2004; Scambos et al., 2004). As the ice

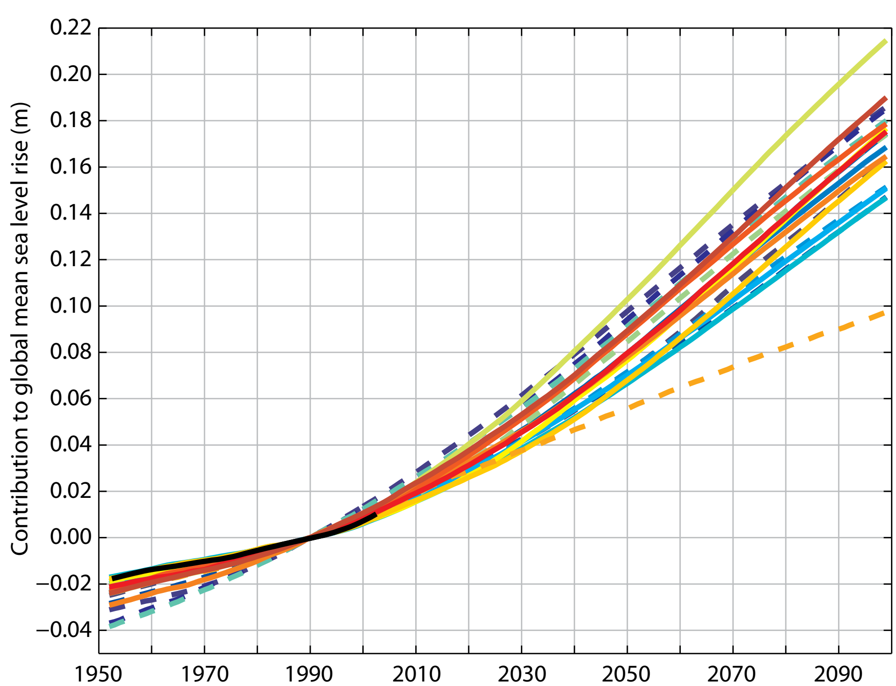

Figure 3. Observations from Cogley (2009; black) and projections of glacier and ice cap contributions to global averaged sea level from 1952 to 2100 for the A1B scenario in the IPCC AR4 and a range of models with (solid) and without (dashed) volcanic forcing.

shelf is a floating extension of the ice sheet, to project these effects therefore requires models of the interaction of ocean and ice shelves as well as of ice sheet dynamics.

There is an important threshold temperature rise for the Greenland Ice Sheet above which increased melting exceeds increased precipitation. For global averaged temperatures, this threshold is estimated to be in the range 1.9–4.6°C above pre-industrial temperatures. If temperatures are maintained above this threshold for millennia, there would be a virtual elimination of the Greenland Ice Sheet (Gregory and Huybrechts 2006). For shorter periods above this threshold, a new equilibrium for a smaller Greenland Ice Sheet may be possible (Charbit et al., 2009; Ridley et al., 2010). As for the ocean, the ice sheets act on long time scales and even after greenhouse gas levels are stabilized in the atmosphere, these changes may be very likely irreversible on any practical human time scale.

> "PERHAPS THE MAJOR CHALLENGE IS THE RESPONSE OF THE ICE SHEETS, PARTICULARLY THOSE PARTS GROUNDED BELOW SEA LEVEL."

Terrestrial Storage

Climate variability and change directly affect the storage of liquid water in the terrestrial environment. However, analyses and simulations for recent decades indicate that while there are short-term variations associated with the El Niño-Southern Oscillation and other climate phenomena, particularly in tropical regions, the multidecadal trend is small (Milly et al., 2003; Ngo-Duc et al., 2005; Biancamaria et al., 2011; Llovel et al., 2011). In contrast, direct human interference in the water cycle by storing water behind dams and depletion of groundwater can be significant. The building of dams is estimated to have offset about 30 mm of sea level rise during the latter half of the twentieth century (Chao et al., 2008). However, the rate of dam building has slowed, and reservoir storage is likely to be approximately stable to 2025 as sedimentation offsets building of new dams (Lettenmaier and Milly, 2009). Groundwater depletion has increased and over the last two decades was likely greater than increases in reservoir storage (Wada et al., 2010, and recent work of Leonard Konikow, US Geological Survey, and colleagues) by up to a few tenths of a millimeter per year. We know of no projections of change in groundwater depletion in this century. Continuation of recent trends would suggest an additional global averaged sea level rise of centimeters.

The Sea Level Budget

Improved observational estimates of all terms have resulted in the sum of contributions more adequately explaining the observations over decadal periods (Domingues et al., 2008; recent work of author Church and colleagues) and since 1993 (Cazenave and Llovel, 2010; Leuliette and Willis, 2011, in this issue). Following author Church and colleagues' recent work, since 1970, ocean thermal expansion and the melting of G&ICs each explain about 40% of the observed rise; the sum of the Greenland and Antarctic contributions and an offsetting contribution from changes in terrestrial storage explain the remaining rise. The thermosteric contribution increased over this period, but cryospheric contributions increased more rapidly. The budget closure for the GRACE period, since 2004, is discussed in Leuliette and Willis (2011, in this issue).

There remains a broad range of projections from the different AOGCMs. The improved agreement between observed and modeled ocean thermal expansion (when all forcing agents are included) evident in Figure 2, the improved closure of the sea level budget for recent decades, and the ongoing Argo and satellite observational programs suggest it is now time to begin to use the observations to constrain projections of thermal expansion for the twenty-first century. For example, a comparison of the upper-ocean heat-content time series and the model simulations from 1950 to 1999 indicates the models without volcanic forcing do not adequately simulate the observed heat content (Figure 2; Domingues et al., 2008). On average, the trends in thermosteric sea level rise are about 10% smaller in the models than the observations, and the warming penetrates deeper into the ocean in the models than in the observations (Domingues et al., 2008; Cai et al., 2010). It should soon be possible to critically evaluate model projections for the twenty-first century. However, it is also clear that there is a need for long (at least multidecadal) time series to robustly constrain the projections.

THE REGIONAL DISTRIBUTION OF SEA LEVEL CHANGE

Ocean Dynamics

Climate models project regional distribution of sea level rise that is mostly related to steric sea level change (Landerer et al., 2007; Pardaens et al., 2011; Yin et al., 2010). In contrast to global averaged steric rise, which is almost entirely thermosteric, the halosteric contributions are significant regionally, often partially offsetting the thermosteric contribution. At least in the HadCM3 (Lowe and Gregory, 2006) and MIROC model (Suzuki and Ishii, 2011), the majority of the steric contribution is related to wind-stress changes; in the MIROC model, this is expressed as the first vertical mode structure of the ocean (heave of the thermocline), with smaller contributions related to higher-order modes and changes in water-mass properties. In contrast, over most of the global ocean, sea level changes associated with redistribution of mass are small. However, over shallow continental shelf areas, there is a significant increase in mass (Landerer et al., 2007; Yin et al., 2010; Suzuki and Ishii, 2010).

Regional variation of sea level rise is on the order of one-third of the global averaged steric expansion in most models and on the order of one-quarter of total sea level rise. However, this distribution is model dependent and there are only limited areas where the mean model departure from the global average change exceeds the intermodel standard deviation, thus limiting the utility of the regional projections. The three most prominent features are the less-than-global-averaged sea level rise in the Southern Ocean, a belt of higher-than-average sea level rise at the poleward extremities of the subtropical gyres, and a greater-than-average rise in the Arctic Ocean, partly as a result of freshening of the water column. Note that recent studies reveal that the response of the Southern Ocean to increased wind forcing is dependent on ocean-model resolution, with coarse-resolution ocean models not adequately representing ocean eddy dynamics (Böning et al., 2008). Also, weakening of the Atlantic overturning circulation leads to a larger-than-global averaged sea level on the northeast coast of North America and other changes in the North Atlantic (Yin et al., 2010; Pardaens et al., 2011). Timmermann et al. (2010) show that decadal changes in wind-stress curl in the Pacific Ocean are consistent with observed sea level trends and that projected wind-stress changes during the twenty-first century lead to local sea level change being slightly less than the global average. For the satellite altimeter period (1993 to present), Merrifield (in press) argues the high rate of sea level rise in the western Pacific corresponds to intensification of the easterly trade winds across the tropical Pacific. Han et al. (2010) argue that strengthening of Indian Ocean Walker and Hadley cells is responsible for a band of minimal sea level rise in the south tropical Indian Ocean. Schwarzkopf and Böning (in press) argue that there is also a significant contribution from the western equatorial Pacific via wave transmission of thermocline anomalies through the Indonesian Archipelago, and their subsequent westward propagation by baroclinic Rossby waves.

Sea level rise from mass contributions to the ocean is communicated rapidly around the ocean by barotropic motions (Gower, 2010; recent work of Katja Lorbacher and colleagues), but the ocean's baroclinic response takes decades (Stammer, 2008). This effect is not yet incorporated in most AOGCM simulations.

Changing Mass Distribution

In addition to these ocean changes, the redistribution of mass from G&ICs and the ice sheets to the ocean results in changes in the loading of Earth (resulting in vertical crustal motion) and changes in the gravitational field (termed sea level fingerprints; Mitrovica et al., 2001, 2009). In the near field (i.e., near to the regions of mass loss from Greenland and West Antarctica as well as concentrated areas of G&ICs), sea level relative to the crust falls, whereas distant from these areas, there is up to a 20–30% larger than global average sea level rise. In addition to the regional changes associated with present-day changes in mass, ongoing changes in relative sea level associated with changes in surface loading over the last glacial cycle (glacial isostatic adjustment, GIA; Davis and Mitrovica, 1996; Milne et al., 2001; Slangen et al., 2011; Tamisiea and Mitrovica, 2011, in this issue) are important.

These regional fingerprints and GIA signals have been combined with steric regional patterns and total sea level rise to make regional projections of sea level rise for particular regions (Katsman et al., 2008) and worldwide (Kopp et al., 2010; Slangen et al., 2011).

To illustrate how we expect future

sea level projections to evolve, following Slangen et al. (2011), here we include global averaged sea level rise, including the rapid ice term, ensemble-averaged regional projections from the AOGCMs, sea level fingerprints using estimates of the mass contributions calculated for the G&ICs, and the Greenland and Antarctic ice sheets for the A1B scenario and the ongoing GIA motions. The G&IC fingerprint was calculated assuming that the spatial pattern of mass loss to the ocean in the twenty-first century would have a similar pattern to that from 1993 to 2007 (Cogley, 2009). The surface mass balance changes over Greenland and Antarctica are assumed uniform in calculating the related fingerprints (Mitrovica et al., in press). One-third of the "rapid ice" contribution is assumed to come from Greenland and two-thirds from the West Antarctic Ice Sheet. For GIA, we use sea level predictions based on the pseudo-spectral algorithm of Kendall et al. (2005), taking into account time varying shorelines, changes in the geometry of grounded marine-based ice, and feedback into sea level of Earth's rotational changes. The ice-load history is based on ICE-5G (Peltier, 2004).

The total projections of sea level change (Figure 4) are nonuniform, with an above-global-average rise in the western Indian Ocean and in a band extending around the oceans at about 40°N and 40°S. In these illustrative projections, the mass redistribution fingerprints and GIA have a significant impact, with substantial falls in sea level (of about 60 cm) in the Arctic and larger rises in the regions adjacent to those glaciated at the time of the Last Glacial Maximum, including the east and west coasts of the United States. Gomez et al. (2010) demonstrate that these regional fingerprint distributions may be an important stabilization factor for the ice sheets because of local sea level fall. In the longer term, these fingerprints are likely to become critically important to regional sea level rise if significant mass loss occurs from the terrestrial cryosphere. Note that in addition to these large-scale climate-related factors, local tectonic motions, such as from sediment compaction following water or petroleum withdrawal, also need to be considered in local impact studies.

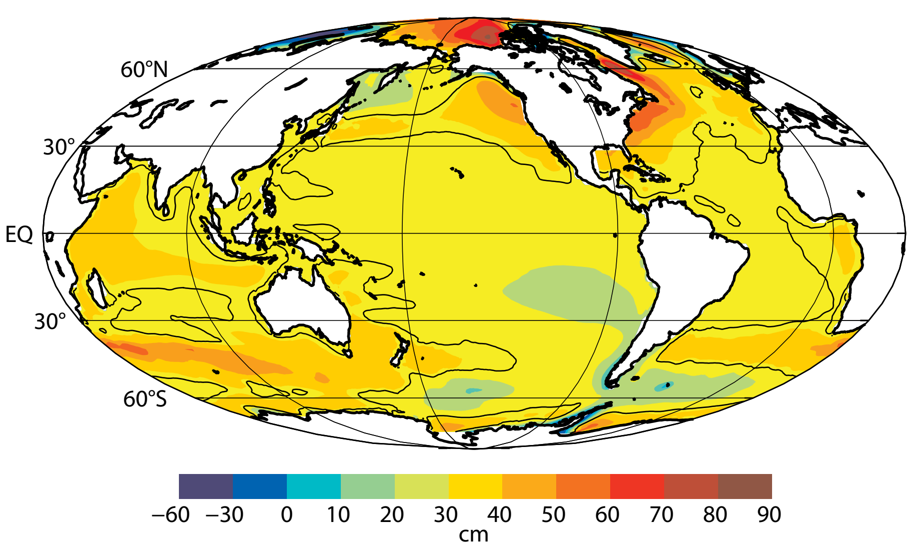

Figure 4. The regional distribution of the projections of sea level change for 2090 compared to 1990, combining global average sea level projections, dynamic ocean departure from the global average, and regional changes associated with the changing mass distribution in the cryosphere. The black contour is the "average" value at 2090 of 38 cm, dividing those regions with above- and below-average sea level rise.

SEMI-EMPIRICAL MODELS

The inability of models to reproduce the observed rise during the twentieth century, our lack of ability to adequately close the sea level budget over decadal periods, and the observation that sea level is currently rising near the upper end of the IPCC projections has led to concern that the IPCC projections for the twenty-first century may be underestimated (Rahmstorf et al., 2007; Figure 1b). This concern has, in turn, led to the development of semi-empirical models (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) in an attempt to bypass our lack of process understanding. These semi-empirical models scale observed sea level rise to some other physical parameter such as global averaged temperature or radiative forcing. They give higher rates of rise and a wider range of projections (about 50–180 cm) by 2100.

A number of concerns have been raised about these semi-empirical projections. First, all the semi-empirical models represent the observed rise over the period of calibration, but there are few independent data available to quantitatively test their predictive skill over decadal periods. When evaluated with climate model simulations, von Storch et al. (2008) found that the parameters in these models varied over time (and even changed sign). Second, because the scaling is completed with the observed rise, any nonclimate-change-related contribution to twentieth-century rise should be removed from the observed rise before the model parameters are determined. Vermeer and Rahmstorf (2009) applied a correction for water stored in dams and GIA, leading to increased projections. However, they did not apply a correction for groundwater depletion or any ongoing ice sheet contribution. Both of these corrections would imply reduced sensitivity and thus smaller projections of sea level change. This scaling of total sea level rise contrasts with the approach of Meehl et al. (2007) where the scaling is done only for the historical sea level rise thought to be associated with rapid ice sheet response and not for other components that are already realistically modeled. Third, the semi-empirical models cannot be expected to reproduce any nonlinear scaling of sea level to other parameters. Two such nonlinear scalings are the reduction of glacier area as the glaciers contract and a reduction in the efficiency of ocean-heat uptake with global warming. Again, both of these physical effects would reduce the semi-empirical model projections.

In summary, although semi-empirical models warn that larger rises in sea level than suggested by current process-based models may be possible, they should be used with caution until there is adequate evaluation of and accounting for the above concerns.

CONCLUSIONS

Over the last decade, there has been significant progress in understanding of future sea level change as a result of improved satellite and in situ observations and their analysis and improved models. As a result, confidence that global averaged sea level is rising and will continue to rise through the twenty-first century and beyond has increased. The amount of rise is dependent on future emissions of greenhouse gases. There are likely to be significant regional differences in the amount of sea level change from both ocean dynamic responses and changes in mass distribution, principally from a changing cryosphere. Better ability to balance the observed sea level budget opens the door for exploring the use of observational constraints to improve projections for the twenty-first century and to attempt probabilistic projections as required for regional impact studies and planning responses.

However, major deficiencies in our understanding remain, and current projections still cover a broad range of values regardless of emission scenarios. Perhaps the major challenge is the response of the ice sheets, particularly those parts grounded below sea level. Observations and modeling studies highlight the importance of ocean/ice shelf/ice sheet/sea level interactions for the stability of ice sheets grounded below sea level. A second set of challenges relates to better understanding of the regional distribution of sea level change, short-term prediction of sea levels, and the impacts of climate change on extreme events.

It is important to recognize that there are important thresholds, such as those leading to ongoing melting of the Greenland Ice Sheet and meters of sea level rise. These thresholds could be crossed in the second half of the twenty-first century if greenhouse gas emissions continue unabated.

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