6 Ocean Temperature and Salinity Contributions to Global and Regional Sea-Level Change

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6.1 Introduction

The oceans are a central component of the climate system, storing and transporting vast quantities of heat. Indeed, more than 90% of the heat absorbed by the Earth over the last 50 years as a result of global warming is stored in the ocean (Bindoff et al. 2007). Understanding how the ocean heat content varies in space and time is central to understanding and successfully predicting climate variability and change.

As the oceans warm, they expand and sea level rises. The amount of expansion depends on the quantity of heat absorbed and on the water temperature (greater expansion in warm water), pressure (greater expansion at depth), and, to a smaller extent, salinity (greater expansion in saltier water). A 1000-m column of sea water expands by about 1 or 2 cm for every 0.1°C of warming. Both the temperature (thermosteric) and salinity (halosteric) contributions (or their combined impact on density (and volume), the steric contribution) are important for regional changes in sea level, but the thermosteric contribution is the dominant factor in globally averaged changes. Ocean thermal expansion, or thermosteric sea-level rise, was a major contributor to 20th-century sea-level rise and is projected to continue during the 21st century and for centuries into the future (Bindoff et al. 2007; Meehl et al. 2007). The close connection between ocean thermosteric sea-level rise and ocean heat-content changes means that understanding sea-level rise will contribute significantly to our understanding of the Earth's total climate system.

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Despite its importance, even the sign of global averaged thermosteric sea-level change was unknown as recently as the 1980s because, in most of the world's oceans, the sampling noise due to mesoscale eddies and interannual variability was too great to determine statistically significant 30-year trends (Barnett 1983). Roemmich (1990) and Joyce and Robbins (1996) described regional, multidecadal increases in steric sea level off southern California and near Bermuda, where long time-series observations were of sufficient duration and temporal resolution for significant results. On basin scales there were a few repeated hydrographic transects, such as at 24° and 36°N in the Atlantic (Roemmich and Wunsch 1984) and at 28° and 43°S in the southwest Pacific (Bindoff and Church 1992), that showed multidecadal warming. Levitus (1990) described decadal variability in the North Atlantic that was at least in part a result of changes in surface winds (Hong et al. 2000; Sturges and Hong 2001; Ezer et al. 1995). In a summary of observational comparisons, Church et al. (2001) found widespread indications of thermal expansion of the order of 1 mm/year, particularly in the subtropical gyres. However, a truly global thermosteric sea-level change estimate was not possible from these widely spaced observations.

A recognition of the importance of the role of the oceans in climate resulted in new global assessments of ocean heat content and thermal expansion. Widespread use of the expendable bathythermograph (XBT) to obtain upper-ocean temperature profiles, beginning in the late 1960s, led to better understanding of the space and timescales of oceanic variability (e.g. Bernstein and White 1979) and of the sampling requirements for global studies (White 1995). The Global Oceanographic Data Archeology and Rescue Project sponsored by the Intergovernmental Oceanographic Commission made an important contribution in assembling and making available the historical data (Levitus et al. 2005d). The World Ocean Circulation Experiment (WOCE) in the 1990s (Siedler et al. 2001) provided the first and highest possible quality, global, top-to-bottom survey of ocean temperature and salinity, as well as repeated transects at a number of key locations. WOCE argued for global altimetric measurements and was also responsible for developing the technology of autonomous profiling floats (Davis et al. 2001), and thus for enabling a global array of profiling floats (the Argo Project; Gould et al. 2004); Argo implementation began in 2000. WOCE obtained about 10 000 high-quality shipboard temperature/salinity profiles over a 7-year period. Argo now collects about the same number of temperature/salinity profiles autonomously, from the sea surface to about 2000 m every month at a fraction of the cost of the WOCE hydrographic survey.

In this chapter, we will assess direct observational estimates of steric sea-level rise for the second half of the 20th century; this is the longest period for which near-global data sets are available (section 6.2). The "era of satellite altimetry", beginning in late 1992 with the launch of the TOPEX/Poseidon radar altimeter satellite, is qualitatively different from the earlier period because of the WOCE global hydrographic survey, repeated XBT sampling along commercial shipping routes, and high-precision satellite altimeters. The latter allows near-global sea-level changes to be measured globally in parallel with the *in situ* measurements of thermosteric sea level. We will also consider the recent record of the Argo Project, with near-global coverage since about 2004.

In addition to the much improved observational database, data-assimilation techniques for combining observations and models that are standard tools for atmospheric reanalyses are now being applied to the ocean. This approach helps overcome the inadequate data distribution and allows synthesis of all available data in one consistent estimate of the evolving ocean. The first generation of these results has recently become available (section 6.3). It is also possible to infer ocean steric changes as the difference between changes in ocean volume (estimated from sea level) and changes in ocean mass (estimated by satellite gravity observations; section 6.4).

Since the 1960s and 1970s, global ocean and coupled atmosphere–ocean general circulation models (AOGCMs) have been developed. These models have improved rapidly as computing power has increased, improved parameterizations, numerical techniques and ocean data sets have been developed and assembled and interest in climate issues has exploded. These models are the basis for the projections of global averaged steric sea-level rise and the regional distribution of sea-level rise during the 21st century and beyond (section 6.5). Note that geophysical processes also affect the regional distribution of sea-level rise (see Chapter 10).

Significant progress in historical assessments and the modeling of steric sea-level rise has been made over the last decade. Improved *in situ* and satellite observational programs that are now operational will lead to further improvements in our understanding, assessments and projections. However, a number of significant gaps remain, including observations of the deep, abyssal, ice-covered and coastal oceans. Uncertainties remain about instrumental biases in historical data sets and there is a need for continued careful quality control of all data sets. Comparisons of observational estimates with climate models are required at global and regional scales to understand the implications for the detection, attribution, and projection of steric sea-level rise. We bring these ideas together in section 6.6 with recommendations for observational and modeling studies.

6.2 Direct Estimates of Steric Sea-Level Rise

6.2.1 The Second Half of the 20th Century

The data distribution is an important issue in estimating steric sea-level rise. Figure 6.1 shows the global inventory of high-quality research ship profiles (station) data to depths greater than 500 m for the 1950s, the 1990s, and for XBT profiles in the 1990s and profiling float data (the Argo Project) from 2000 to September 2007. The strong Northern-Hemisphere bias in the pre-Argo data sets is apparent, with enormous data-void regions in the two-thirds of the ocean in the Southern Hemisphere. The poor data distribution means that any global

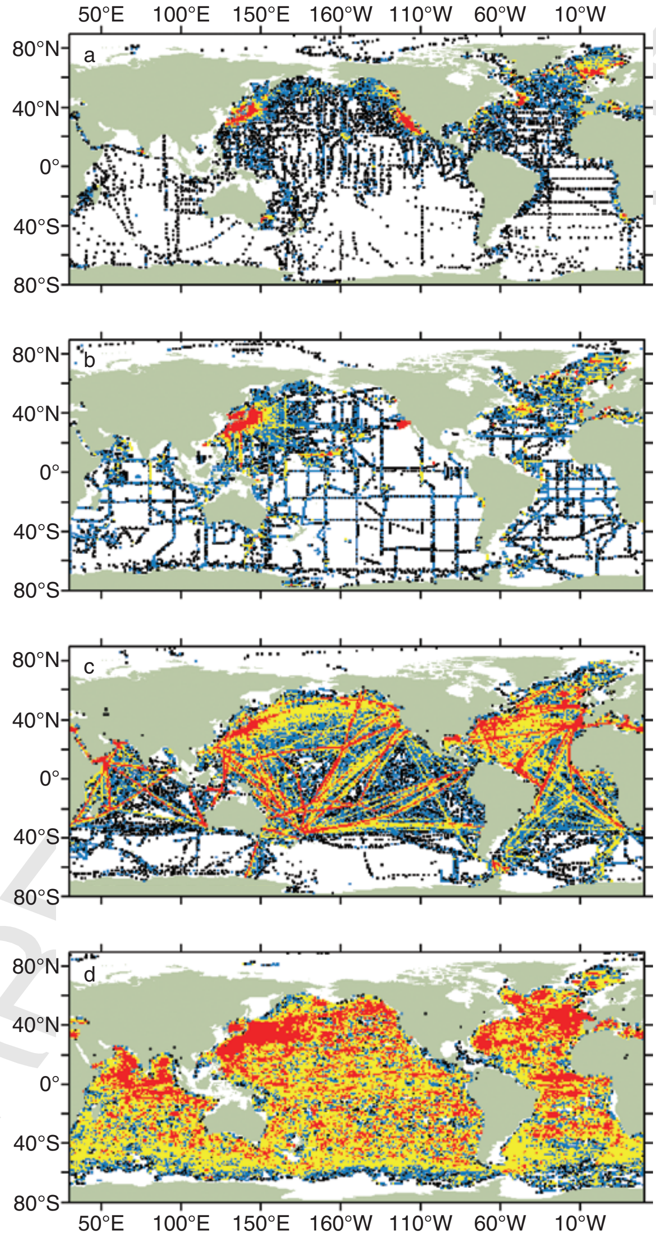

Figure 6.1 Distribution of ocean station data with temperature measurements to depths greater than 500 m. For stations (a) in the 1950s (about 46 600 total stations) and (b) in the 1990s (about 65 590 total stations); (c) XBT profiles in the 1990s (about 278 000 stations); and (d) for Argo data through September 2007 (about 368 000 stations). The number of stations in each 1-degree square is indicated by color: white = 0 stations, black = 1 station, blue = 2–5 stations, yellow = 6–20 stations, red = more than 20 stations. (Information sources: NODC and Argo Global Data Assembly Center.)

estimates will be reliant on the chosen scheme for filling data voids in space and time.

Global investigations of ocean heat storage and thermosteric sea-level rise starting from 1950 were performed by Levitus and colleagues (Levitus et al. 2000, 2005a, 2005b; Antonov et al. 2002, 2005) and by Ishii and colleagues (Ishii et al.

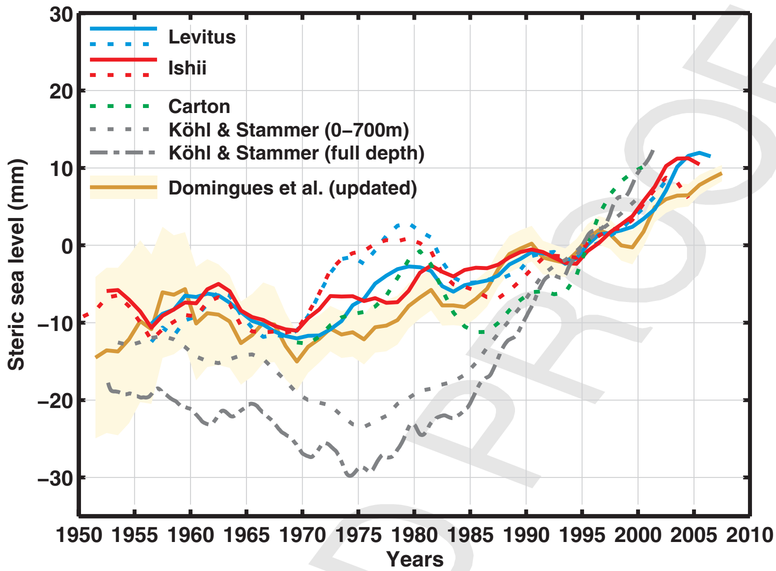

Figure 6.2 Multi-decadal direct estimates of globally averaged thermosteric sea-level changes for the upper ocean (0–700 m). The dotted lines are the thermosteric estimates of Levitus et al. (2005a) and Antonov et al. (2005; blue dotted line), Ishii et al. (2006; red dotted line), and from the Simple Ocean Data Analysis (SODA) model (Carton et al. 2005; green dotted line, to 1000 m) using XBT data not corrected for fall-rate errors. The solid lines are the equivalent curves after the XBT biases have been corrected (Levitus et al. 2009; Ishii and Kimoto 2009), with the addition of an updated estimate of Domingues et al. (2008; brown line with one standard deviation error estimates shown by the shading). The gray lines are the steric estimates from Köhl and Stammer (2008) to 700 m (gray dotted line) and full depth (gray dashed/dotted line).

2003, 2006). The World Ocean Database (WOD; Conkright et al. 2002 and later updates) forms the basis for these and other estimates, but the analyses differ in their quality-control procedures, inclusion of recent profiles, depth coverage, and analysis techniques.

A number of these results are summarized in Figure 6.2. For the 0–700 m layer and from 1955 to 2003, Levitus et al. (2005a) estimated a heat-content trend of $(0.23 \pm 0.06) \times 10^{22}$ J/year and Antonov et al. (2005) estimated the corresponding thermosteric sea-level rise of 0.33 ± 0.04 mm/year. For the same layer and time period, Ishii et al. (2006) estimated a linear trend of global-ocean heat-content increase of $(0.19 \pm 0.05) \times 10^{22}$ J/year for 1955–2003, with a corresponding rise of 0.36 ± 0.07 mm/year in thermosteric sea level. Consideration of the 0–3000 m depth range increased the estimate of Antonov et al. by approximately 20%, to 0.40 ± 0.05 mm/year for the period 1957–97.

Lombard et al. (2005; see also Levitus et al. 2005c) compared the analyses by the above two groups and found them to be similar, with much of the apparent interannual-to-decadal variability correlated with climate phenomena: the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation, and the North Atlantic Oscillation (NAO). While these analyses are consistent with one another, the sparse sampling, particularly in the Southern Hemisphere, and instrumental biases (see below) raise questions about their accuracy.

Optimal interpolation methods, applied in several of the above analyses, assume zero anomaly in data-void regions. Gille (2008) showed that these sampling problems are very significant in the Southern Ocean and concluded that thermosteric sea-level rise is likely to have been significantly larger than the above estimates. This conclusion is supported by tests using numerical models. Assuming zero temperature anomaly in unsampled regions resulted in small trends whereas assuming that the same average anomaly at a given time occurred in sampled and unsampled regions gave much larger trends (Gregory et al. 2004).

Instrumental biases are also a major source of uncertainty. Gouretski and Koltermann (2007) demonstrated that Mechanical Bathy Thermographs and XBTs (which dominate the historical data archive and were not designed for climate purposes) have time- and depth-dependent biases of as much as 0.4°C. Wijffels et al. (2008) and Ishii and Kimoto (2009) demonstrated that the XBT biases are dominated by inaccuracies in the depth of observations caused by errors in the estimated XBT fall rate and that these fall-rate errors change from year to year (probably as a result of small manufacturing differences from one batch to the next) but coherently around the globe, allowing an approximate correction to be applied to the historical data. One difficulty in this process is the lack of metadata specifying what XBT data were previously adjusted using the earlier Hanawa et al. (1995) fall-rate correction.

Recent Estimates of Thermosteric Sea Level

Domingues et al. (2008) addressed both instrumental and sampling biases by applying the Wijffels et al. (2008) fall-rate corrections to the global ocean data set of Ingleby and Huddleston (2007) and using a reduced-space, optimal-interpolation (RSOI) technique (Kaplan et al. 2000) to interpolate across data voids. Tests of the RSOI technique using non-eddy-resolving climate model simulations demonstrated that the errors in global averaged thermosteric sea level of the upper 700 m resulting from the spatial sampling in this database are mostly less than about 5 mm after 1960 (N.J. White et al., personal communication). The unresolved eddy variability is likely to increase these error estimates somewhat. For the period 1961–2003, the estimate of Domingues et al. (2008) of ocean thermal expansion for the upper 700 m was 0.52 ± 0.8 mm/year (i.e. a linear trend about 50% larger than earlier results; Figure 6.2). The results do not have the large decadal variability of earlier estimates (particularly the "hump" of the 1970s and 1980s). Instead they show little thermosteric rise prior to the mid-1970s, then a steady rise and variability that appears to be at least partly associated with volcanic eruptions (section 6.5).

The revised estimates of Levitus et al. (2009) and Ishii and Kimoto (2009) used different XBT bias corrections and are generally within the error bars of the results of Domingues et al. All of these analyses show little change from the 1950s to the mid-1970s and then a rise, which in the Levitus et al. and Ishii and Kimoto analyses accelerates in the mid-1990s. Over the longest time span available of 1951–2005, Ishii and Kimoto (2009) found a linear thermosteric trend of 0.29 ± 0.05 mm/year. These revised estimates are quite different from past estimates thus strengthening the argument that the 1970s peak is most likely a result of instrumental biases in earlier analyses (e.g. figure 15 in Wijffels et al. 2008). However, some smaller differences between these estimates are present;

for example the Domingues et al. series has what appears to be an anomalous minimum about 2000. With the inclusion of the most recent version of Argo data (Barker et al., unpublished work), the updated (from 2000) estimate of Domingues et al. indicates warming and expansion continues (but at a slower rate) to the end of the record. In contrast, the Levitus et al. and Ishii and Kimoto time series, which have included some corrections to early problems identified in the Argo data but not the more subtle biases identified by Barker et al., indicate a leveling off in the thermosteric sea level. Clearly further analysis and careful quality control of data is required to refine the multidecadal estimates.

Inferred Changes in Ocean Mass from Changes in Ocean Salinity

Antonov et al. (2002) and Ishii et al. (2006) estimated a global average halosteric component (expansion/contraction of ocean waters caused by changes in salinity) of 0.05 ± 0.02 and 0.04 ± 0.01 mm/year, over the 1957–94 and 1955–2003 periods, respectively. However, while the halosteric contribution is quantitatively important in the regional patterns of sea-level change, it does not contribute significantly to a global average steric change. It is instead an indication of freshening and thus of an increase in the mass of the ocean (Antonov et al. 2002; Munk 2003). This estimate of change in ocean mass is complementary to estimates inferred from changes in the storage of ice and water on land (Chapters 7 and 8) and the difference between total sea-level change and the steric component (section 6.4). The Antonov et al. (2002) estimate of the decrease of global salinity from 1957 to 1994 implied an increased mass equivalent to a sea-level rise of 1.3 ± 0.5 mm/year, if the source of the fresh water was assumed to be continental ice. However, Wadhams and Munk (2004) estimate melting of sea ice was responsible for over half of the observed freshening and thus the mass contribution to sea-level rise was estimated as about 0.6 mm/year, approximately consistent with the contributions of glaciers and ice caps, with a small contribution from the ice sheets (Chapter 7). However, measurement inaccuracies, inadequate estimates of changes in sea-ice volume and sparse ocean sampling (much poorer than for temperature) mean the quoted error estimates for freshening of the ocean are likely to be (unrealistic) lower bounds. As a result, the estimated multidecadal rates of changes in ocean mass inferred from salinity changes for the second half of the 20th century should be considered with caution. Projected increases in the cryospheric contribution to sea-level rise would lead to a larger change in ocean mass and a larger reduction in ocean salinity than during the 21st century.

6.2.2 The "Era of Satellite Altimetry"

The 1990s was marked by improvements in the sampling of the oceans by hydrographic and XBT networks and also the advent of high-precision satellite altimetry which provides an accurate determination of global sea-level patterns and trends. Altimetric height is highly correlated with heat content and steric height (White and Tai 1995; Gilson et al. 1998; Willis et al. 2003, 2004) and this correlation can be exploited both to assess the sampling error of the sparse *in situ* networks and to attempt to correct it (Willis et al. 2004).

Global estimates of heat content (0–750 m) and thermosteric height were completed by Willis et al. (2004) using *in situ* data alone and in combination with altimetric height. For 1993–2003 they found a thermosteric (0–750 m) sea-level rise of 1.6 ± 0.3 mm/year. From the combined *in situ* and altimetric database constructed by Guinehut et al. (2004), Lombard et al. (2006) estimated a thermosteric sea-level rise of 1.8 ± 0.2 mm/year over 1993–2003. These values are significantly larger than estimates based on *in situ* data alone (1.2 ± 0.2 mm/year; Antonov et al. 2005), possibly a result of too large a weight given to altimetry data in the Willis et al. and Lombard et al. analyses. However, it is now clear that this and indeed most of the observational estimates for the 1990s were affected by XBT fall-rate errors (Wijffels et al. 2008). Significant differences remain, even with the XBT fall-rate corrections applied. The thermosteric rise estimates for 1993–2003 are 0.8 ± 0.4 mm/year (Domingues et al. 2008), 1.3 ± 0.4 mm/year (J.K. Willis, personal communication), 1.5 ± 0.4 mm/year (Ishii and Kimoto 2009), and 1.1 ± 0.4 mm/year (Levitus et al. 2009). Further efforts are underway to agree on the best approach to correct the XBT biases.

The regional linear trends of thermosteric sea-level change for 1993–2003 for both Willis et al. (2004) and Domingues et al. (2008) are similar, with the latter being smoother because it only contains large spatial-scale variability (Figure 6.3; and Church et al. 2008). Both are similar to the regional trends in altimeter-measured sea level over the same period, demonstrating the importance of thermosteric changes for the regional distribution of sea-level rise (Figure 6.3; also see, for example, Lombard et al. 2005). The change in the tropics is largely associated with interannual variability associated with the ENSO phenomenon. The maxima in zonally integrated steric height increase at 38°N and 40°S may be a result of the increase of the atmospheric annular modes resulting in enhanced Ekman convergence and downward displacement of isopycnals at these latitudes (Roemmich et al. 2007).

One anomalous aspect of the altimetry era is that it was preceded by the explosive volcanic eruption of Mt Pinatubo in June 1991. Climate models (section 6.5; Church et al. 2005; Gregory et al. 2006; Domingues et al. 2008) indicate that sulphate aerosols injected into the stratosphere by violent volcanic eruptions such as Mt Pinatubo (and the earlier Mt Agung (1963) and El Chichon (1982) eruptions) reflect solar radiation, leading to a (rapid) cooling and thermal contraction of the oceans (about 3×10^{22} J and 5 mm) over roughly an 18-month period. The recovery of the climate system is much slower, taking decades (Church et al. 2005; Gregory et al. 2006) or even centuries (Gleckler et al. 2006a, 2006b). It is possible that the recovery from the Mt Pinatubo eruption may be partly responsible (about 0.5 mm/year) for the enhanced rate of warming and sea-level rise seen in the subsequent years (Church et al. 2005; Gregory et al. 2006).

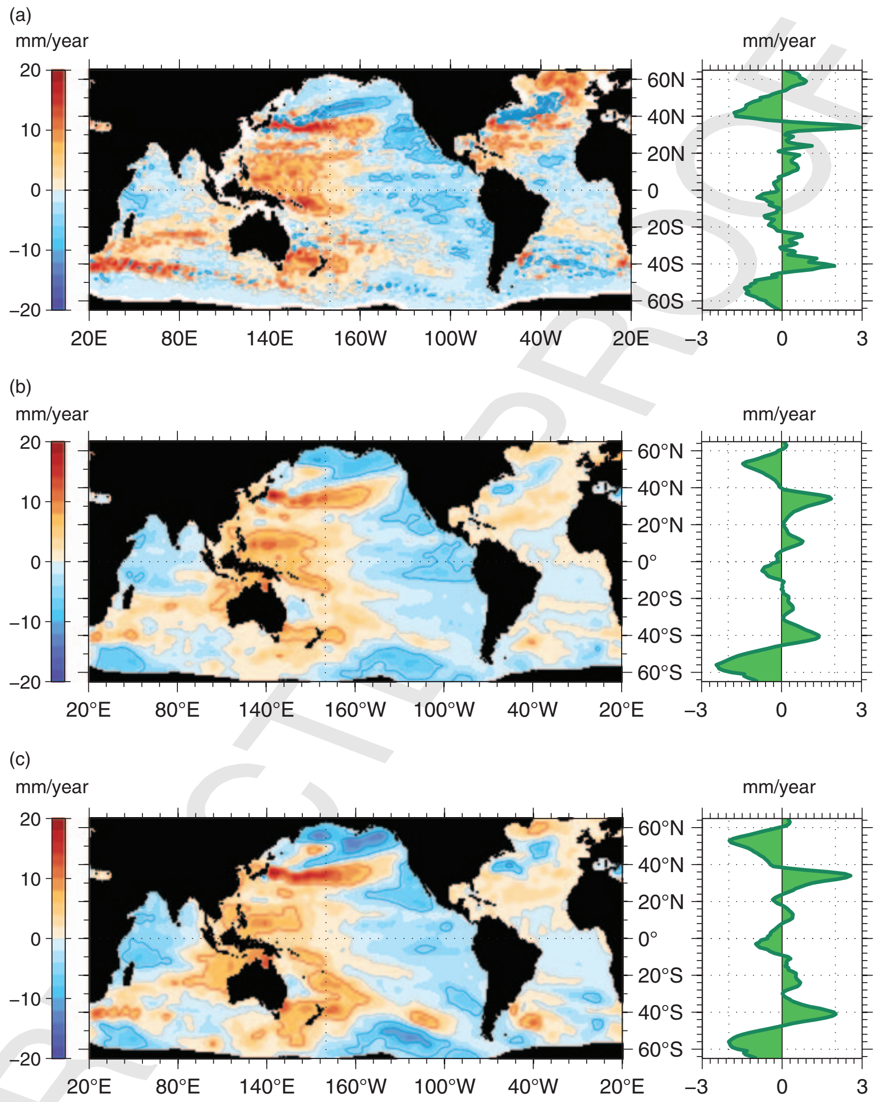

Figure 6.3 Regional distribution of thermosteric sea-level rise (mm/year) for the period 1993–2003, from the results of Willis et al. (2004; upper panel), Domingues et al. (2008) and Church et al. (2008; middle panel) and, for sea level from the satellite altimeter data (bottom panel). Panels on the right show the zonally averaged values. Note that all data are departures from the global averaged rise.

6.2.3 Progress and Gaps in the Ocean-Observing System

While the 1990s observations overcame some of the sampling problems of the previous era, significant issues remained. The WOCE survey was global, but its one-time character meant that the XBT networks (Figure 6.1) bore the main responsibility for temporal sampling. The 750-m depth range of the T-7 XBT set the limit for the heat-content estimates of Willis et al. (2004) and Domingues et al. (2008). Deeper estimates such as Antonov et al. (2005) rely on the much sparser hydrographic data sets.

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Many of these problems are being significantly reduced as a result of the Argo Project (Gould et al. 2004), in which an array of autonomous floats (each with a lifetime of 3–5 years) provide temperature and salinity profiles for the upper 2000 m of the global ocean using high-quality sensors (Figure 6.1d). As of early 2008, the Argo array reached the design level of about 3000 instruments. There has been near-global coverage since 2004. Argo is now producing over 100 000 globally distributed temperature/salinity profiles per year, mostly to depths of 2000 m, and with data accuracy an order of magnitude better than XBTs but not quite the same standard as research-ship observations. It does so with better spatial coverage than the WOCE survey and it greatly reduces the Northern Hemisphere and summertime biases inherent in all previous hydrographic data sets. However, users should be aware that near-real-time Argo data are subject to only crude quality checks, and some problems identified are now being corrected in delayed-mode processing. For example, the reported upper ocean cooling since 2003 (Lyman et al. 2006) was an artifact of the transition from XBT sampling (biased warm due to fall-rate error) to Argo sampling (biased cool by the erroneous reporting of pressure in some of the Argo floats; Willis et al. 2009). Barker et al. (unpublished work) identified further inconsistencies in the Argo data (metadata, quality control, drifts in pressure sensors) that can affect thermosteric sea-level estimates. Measures are in place to eradicate the inconsistencies from the Argo data set.

In the deep and abyssal waters, below the depth of the maximum Argo float depth (2000 m) and the maximum depth of the Antonov et al. (2005) analysis (3000 m), recent results have also shown rapid warming (Fukasawa et al. 2004; Johnson and Doney 2006; Johnson et al. 2007, 2008). The warming is largest in the South Atlantic, South Pacific, and southern Indian Oceans, closer to the locations where the properties of these waters were set by their interaction with the atmosphere and the cryosphere in the high-latitude Southern Ocean. The sparse sampling precludes global estimates at this stage, but we must consider the full ocean depth (which is, on average, more than 3500 m) when estimating sea-level rise. Information about the deep and abyssal ocean is also important for understanding the climate system's sensitivity to increasing greenhouse gas concentrations. Designing and implementing an adequate deep-ocean-observing system is a high priority. Similarly, improved observations in ice-covered regions, marginal seas, and coastal areas are required.

6.3 Estimating Steric Sea-Level Change Using Ocean Syntheses

Changes in ocean conditions can also be assessed using data-assimilation techniques. The Simple Ocean Data Analysis (SODA) model (1.2 and 1.4.2; Carton et al. 2005; Carton and Giese 2008) uses an inexpensive multivariate sequential data-assimilation approach in which the model is strongly forced toward observed ocean temperature and salinity from the World Ocean Data Base (Conkright et al. 2002 and later updates) and the Global Temperature-Salinity Profile Program (Wilson 1998). Ocean dynamics and other properties are not preserved in this approach, and the resultant steric estimates from 1968 to 2001 are similar to the direct observational estimates of the original Antonov et al. and Ishii et al. (Figure 6.2) and other similar analyses (Carton and Santorelli 2008). All these results appear to be affected by the time-dependent XBT fall-rate errors.

A more sophisticated approach to estimate the evolving state of the ocean is to synthesize the available data into a dynamically consistent model using the adjoint assimilation technique (for example Köhl et al. 2007). The model then carries the information, obtained locally in space and time, forward and backward in time over many years and decades. This allows, in principle, the possibility of inferring the ocean state and its changes even in locations remote from direct observation and of rejecting potentially spurious observations that are not dynamically consistent with other data or the surface forcing.

Relevant studies include the 50-year-long syntheses (Köhl and Stammer 2008), as well as many efforts covering the last 14 years (e.g. Köhl et al. 2007; Wunsch et al. 2007; Wenzel and Schröter 2007). The time series of thermosteric sea level of Köhl and Stammer (Figure 6.2) shows an initial decrease until about 1975 and then a larger rise reaching 1.8 mm/year (1.2 mm/year over the upper 750 m) from 1992 to 2001. From 1961 to 2001, the average rise is 0.92 mm/year, with 0.66 mm/year occurring in the upper 750 m. The largest difference between these results and the direct observations is the greater fall in the first 25 years and the larger rise in subsequent decades, including in the 1990s.

Figure 6.4 shows the associated regional linear trends of the steric sea level estimated from the 50-year results for 1962 through 2001 (Köhl and Stammer 2008). The patterns suggest major changes in the Southern Ocean and smaller changes in the tropical and subtropical oceans. However, note that these are early attempts at ocean reanalysis and that significant challenges remain. For example, the results of Köhl and Stammer (2008) imply an enormous and clearly unrealistic freshwater flux out of the ocean of 10 ± 13 mm/year for 1962–2002. Although there is a small impact on steric sea level compared with regional-scale changes, until an adequate global water cycle is included in these reanalyses estimated changes of the mass of the ocean will be unrealistic. Also, estimates of large-scale integral quantities are sensitive to initial model adjustments and results obtained from simulations commencing from 1993 are quite different during the first few years from those obtained from the 50-year estimate. The long memory of the system underlines the need for ocean synthesis efforts covering decades.

There are significant differences between the various reanalysis products and between these products and the direct observational results. Ocean reanalysis has only been an active research topic since the advent of WOCE in the 1990s. Over time, increasing fidelity of such ocean synthesis efforts should lead to the best possible basis for studies of decadal sea-level and heat-content changes.

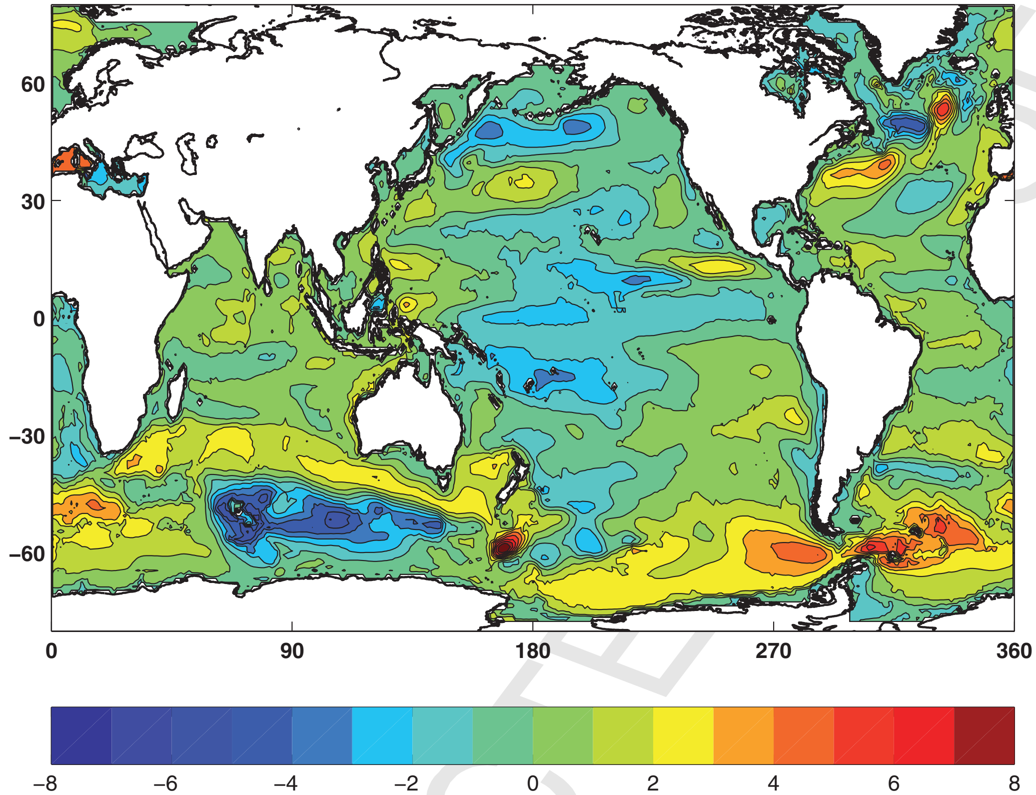

Figure 6.4 Sea-surface height trend in millimeters per year estimated from the data assimilation of Köhl and Stammer (2008) for the period 1962–2001.

6.4 Inferring Steric Sea Level from Time-Variable Gravity and Sea Level

The redistribution of water on the Earth causes temporal variations in the Earth's gravitational field (e.g. Wahr et al. 1998; Chapters 7 and 8). The Gravity Recovery and Climate Experiment (GRACE) satellite mission, launched in March 2002, has sufficient accuracy to resolve monthly movements of water on a spatial resolution of several hundred kilometers (Tapley et al. 2004).

GRACE ocean-mass estimates can be combined with sea-level measurements (of ocean volume; Chapter 5) to infer the steric component. This has been demonstrated for the seasonal variation (e.g. Chambers et al. 2004; Chambers 2006; Willis et al. 2008) and to estimate the seasonal exchange of water between the ocean and land (Figure 6.5), as previously calculated from combinations of sea-level data and hydrological models (Chen et al. 1998; Minster et al. 1999; Cazenave et al. 2000; Chapter 8). Unlike the previous studies, GRACE provides a direct

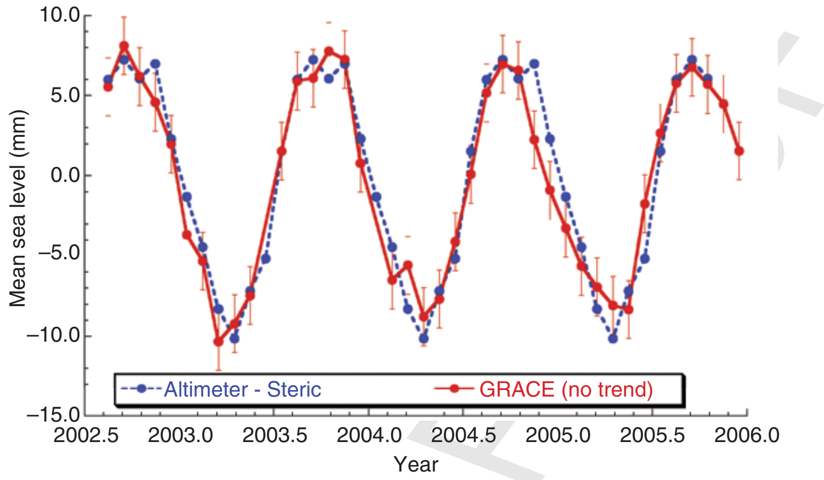

Figure 6.5 Mass component of sea level measured by GRACE (with 3-year trend removed; red), and the inferred seasonal climatological signal computed from 11 years of altimetry and steric sea level from the World Ocean Atlas 2001 (Chambers et al. 2004).

measure of changes in ocean mass. By comparing the GRACE gravity estimates with steric-corrected altimetry, Chambers et al. (2004) argued that the GRACE monthly ocean-mass estimates are accurate to about 1.8 mm equivalent sea level.

Initial attempts to estimate interannual steric sea-level variations (Lombard et al. 2007) found a positive altimeter/GRACE-derived steric sea-level trend between 2003 and 2005, in disagreement with the Lyman et al. (2006) estimates based on hydrographic data, again highlighting that the reported ocean cooling was an artifact of instrumental biases. Recently, Willis et al. (2008), Cazenave et al. (2009), and Leuliette and Miller (2009) tested the consistency of the three independent measurements of ocean mass and steric change. They used altimeter data for the total sea level, Argo data for the steric contribution, and gravity data for mass change. The seasonal signals of the detrended time series agreed within the error bars (Willis et al. 2008). However, Willis et al. found a significant inconsistency between the three measurements in the trend from mid-2003 to mid-2007, indicating a remaining systematic bias in one or more of the complementary observing systems. In contrast, Cazenave et al. used a different and larger glacial isostatic adjustment (GIA; the movement of the "solid" Earth in response to changes in the distribution of ice and water; see Chapter 10) from the Peltier and Luthcke (2009) GIA model, and managed to close the budget over the 2003–2008 period, highlighting the importance of accurate GIA estimates. Using a slightly later period (better Argo coverage), the same GIA correction as Willis et al. but different processing for the altimeter data, Leuliette and Miller (2009) also managed to close the sea-level budget. Note that all of these comparisons are for very short periods and that more rigorous and useful comparisons will be possible in several years when the time series are longer.

The long-term trends from the short GRACE data face several challenges. Although the instrumental error is only ±0.3 mm/year, significant uncertainty in the long-term rate estimate is also a result of uncertainty in GIA, geocenter changes, and interannual variability.

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GIA causes an apparent decrease in the GRACE estimate of ocean mass trends that is related to movement of the "solid" Earth and unrelated to sea-level rise. The Paulson et al. (2007) GIA model, developed using the ICE-5G ice history (Peltier 2004) and a range of upper and lower mantle viscosities that produce good agreement with GRACE measurements over Hudson Bay and Fennoscandia, results in an estimated correction most likely between +1.0 and 1.5 mm/year (Willis et al. 2008), somewhat lower than the correction used by Cazenave et al. (2009) from the GIA model of Peltier and Luthcke (2009).

Ocean-mass variations measured by GRACE are sensitive to the position of the center of the Earth (geocenter) which GRACE does not measure. Seasonal geocenter variations can be estimated from other satellite tracking data (e.g. Cretaux et al. 2002), and are accurate enough to use in seasonal analysis of GRACE data (Chambers et al. 2004; Chambers 2006). Unfortunately, the geocenter interannual *trend* is poorly known as it is difficult to separate from vertical rates at the latitudinally asymmetric distribution of tracking stations used to compute the time series. Swenson et al. (2008) have recently proposed a method to estimate interannual and seasonal variations in geocenter from a combination of GRACE data and ocean models that holds promise to improve our knowledge, at least during the time of the GRACE mission.

Ocean-mass changes occur on all timescales with significant seasonal and interannual fluctuations in runoff, precipitation and evaporation. Nerem et al. (1999) estimated that seasonal exchange of water between the ocean and land-based reservoirs causes global averaged sea-level fluctuations of about ±8 mm. ENSO causes worldwide changes in precipitation and evaporation. Chambers et al. (2000), Willis et al. (2004), and Ngo-Duc et al. (2005) suggest a significant ocean-mass variation associated with the 1997 ENSO event, equivalent to about 5 mm over a 2–3 year period. These would imply the 95% confidence interval for trends of sea level for 3 years of data is about ±2.8 mm/year. Recent modeling studies (Landerer et al. 2008) suggest a somewhat smaller variation in ocean mass in response to ENSO events and would imply a smaller confidence interval.

If sufficiently long (decadal) time series are collected, these three uncertainties are small enough that GRACE and follow-on missions have the potential to measure the rate of ocean-mass change to the same order of accuracy as altimetry observes the total sea-level rise.

6.5 Modeling Steric Sea-Level Rise

Significant efforts have been made to simulate 20th-century climate and project 21st-century climate using coupled AOGCMs. These studies have been coordinated by the World Climate Research Programme and used in the Assessments of the Intergovernmental Panel on Climate Change (IPCC). The models are also used to understand the factors controlling sea-level change and to estimate projections of global mean and regional sea-level change.

Simple climate models and Earth system models of intermediate complexity are also used to estimate ocean thermal expansion. The most widely used simple climate models (MAGICC; see http://www.cgd.ucar.edu/cas/wigley/magicc/) represent the ocean as a one-dimensional (vertical) model in which heat diffuses vertically into the ocean. These models are generally tuned to represent AOGCMs or observed ocean time series. The prime value of simple climate models and Earth system models of intermediate complexity is to explore the sensitivity of sea-level-rise estimates to various climate parameters and to estimates sea-level rise (and other climate variables) for a broader range of greenhouse gas scenarios than is possible with AOGCMs (see for example Church et al. 2001). We will not discuss these models further here.

A number (although not all) of the most recent AOGCM simulations do not rely on artificial surface flux adjustments to yield a stable climate, as required in earlier simulations (e.g. Bryan 1996). As the steric sea-level anomalies depend directly on the surface fluxes, doing without artificial flux adjustments renders estimates more robust. However, many (if not all) of the models still drift at rates up to about 1 mm/year (Katsman et al. 2008) in the global average, as a result of slowly changing temperature and salinity fields of the deep ocean. The departure of the local trends from the global average can be of similar magnitude to the global averaged trends, especially at high latitudes (D. Monselesan, personal communication). To remove this residual drift, model estimates of sea-level change from natural and anthropogenic forcing of climate for the 20th and 21st centuries are usually compared with a simulation in which these time-variable forcing factors are not included (the control simulation). As the thermal expansion coefficient is a function of temperature, the thermal expansion anomalies computed from coupled AOGCMs depend (weakly) not only on the offset relative to the real ocean but also on the drift rate of the control climate. Furthermore, the inherent assumption of linear separability of climate signals and model drift when calculating anomalies of scenarios relative to the control climates may introduce (probably small) errors. Gille (2004) has also pointed to the sensitivity of global averaged sea-level change to inaccurate isopycnal and vertical diffusion parameters in models, but suggested the effect is small.

The spatial variability of steric sea-level change is linked to ocean dynamic processes, in particular to the redistribution of heat and salt horizontally and vertically through air–sea exchange and the ocean circulation. To the extent that the various AOGCMs differ in their ability to simulate the respective processes, the simulated global mean as well as regional sea level will differ, as discussed below.

Geophysical processes associated with the changing distribution of mass of the Earth system (for example, loss of mass from ice sheets and the resultant change to the Earth's gravity field and the associated crustal motion; Mitrovica et al. 2009) will also affect the regional distribution of sea-level rise. These processes must be accounted for separately to the climate factors discussed here. See Chapter 10 for further discussion of these effects.

6.5.1 Comparison of Observed and Modeled Global Averaged Thermosteric Sea-Level Rise

A number of studies (for example Levitus et al. 2001; Barnett et al. 2001, 2005; Gent and Danabasoglu 2004; Hansen et al. 2005) have shown that the observed rate of ocean warming since 1950 (and by implication thermosteric sea-level rise) is not a result of natural variability alone and that increases in greenhouse gas concentration have contributed significantly. Using 500-year simulations, Gregory et al. (2006) show that the rate of thermosteric rise is larger during the 20th century than previous centuries as a result of anthropogenic forcing and show that the combination of natural and anthropogenic forcing is critical for simulating the evolution of thermosteric sea-level rise during the 20th and 21st centuries.

For 1961–2000, the models, none of which assimilates observed ocean data, approximately reproduce the most recent thermosteric sea-level variability in the upper 700 m when the models are forced by all climate forcing factors, including time-variable volcanic and solar forcing (Figure 6.6; Domingues et al. 2008). Although there are considerable differences between the simulations, on average the multidecadal trends are smaller than observed. The models without volcanic

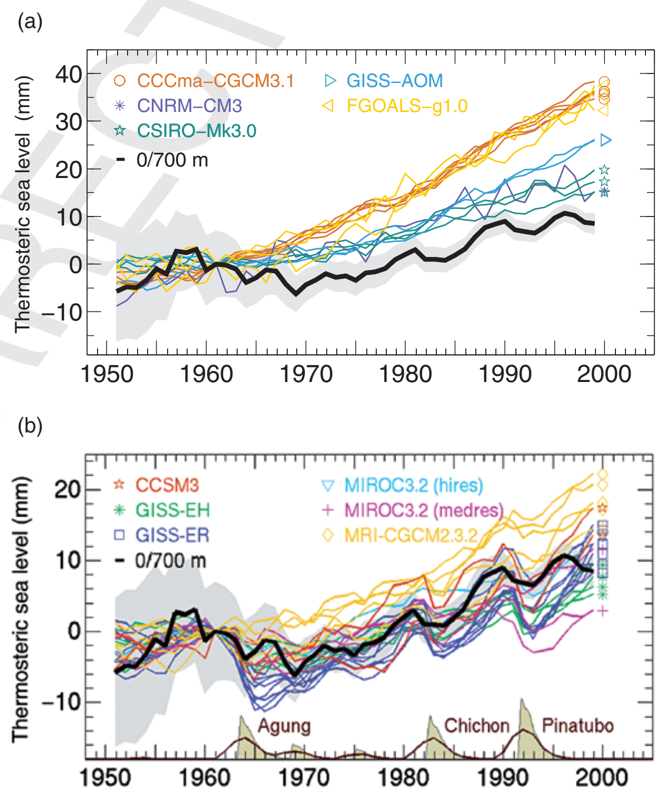

Figure 6.6 Observed and modeled global averaged ocean thermal expansion for the upper 700 m from 1950 to 2000. The models in (a) are those that include time-variable greenhouse gases, aerosols, and solar but no volcanic forcing. The models in (b) also include volcanic forcing. The observations are from Domingues et al. (2008; black with 1σ error estimates). The stratospheric loadings from major volcanic eruptions are indicated along the bottom with the brown curve a 3-year running average of these values. See Domingues et al. (2008) for more details.

forcing have less variability than observations and substantially larger trends. The comparisons clearly demonstrate the importance of volcanic eruptions (indicated on the bottom panel in Figure 6.6) for ocean heat content and thermosteric sea-level variability. The smaller trends in the models with volcanic forcing are consistent with cold anomalies persisting in the ocean for many decades after the eruptions (Delworth et al. 2005; Glecker et al. 2006a, 2006b; Gregory et al. 2006) and thus slowing the rate of 20th-century sea-level rise and partially masking any acceleration in sea-level rise (Church and White 2006). The models do not support the pronounced warming in the 1970s (Figure 6.2) and subsequent cooling in the 1980s present in the early analyses and that recent observational analyses now suggest is spurious (Wijffels et al. 2008; Domingues et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009). The approximate agreement between the modeled and observed estimates of ocean thermal expansion opens up the possibility of using the observations to constrain projected sea-level rise by either choosing between different models or the weighting of model results. This is likely to be an avenue pursued in the fifth IPCC Assessment.

6.5.2 Projections of Steric Sea-Level Change

Projected steric sea-level rise is a function of changes in atmospheric greenhouse gas concentrations and other climatic forcings and varies considerably between models. Comparing the last decade of the 21st century with 1980–2000, the global mean thermal expansion is estimated to be from 10 to 24 cm for the B1 SRES greenhouse gas scenario, 13 to 32 cm for the A1B scenario, and 17 to 41 cm for the A1FI scenario (Meehl et al. 2007). The climate sensitivity of the coupled models and their ocean heat-uptake efficiency (Raper et al. 2002) are important factors contributing to the differences between models. Gregory and Forster (2008) found the climate sensitivity and the heat-uptake efficiency were independent of each other in the models used in the 2007 IPCC Assessment. Since the ocean's thermal inertia is large, the ocean (especially the deeper layers) will continue to take up heat (resulting in steric sea-level rise) for centuries and even millennia after greenhouse gas concentrations have stabilized in the atmosphere. Contributions to steric sea level could eventually reach several times the value at the time when greenhouse gas concentrations are stabilized (Meehl et al. 2007). For example, for simulations with concentrations stabilized at the A1B level in 2100, thermal expansion during the 22nd century will be of similar magnitude to that for the 21st century and by 2300 could be in the range 30–80 cm (Meehl et al. 2005, 2007).

The steric sea-level changes in climate models and observations are not spatially uniform and some regions are projected to experience more than twice the global average rate of steric rise (e.g. Gregory et al. 2001; Gregory and Lowe 2000; Lowe and Gregory 2006; Meehl et al. 2007; Suzuki et al. 2005; Landerer et al. 2007a; Figure 6.7). Though different models predict different distributions, there are some common features. Many models show a strong sea-level rise in the Arctic

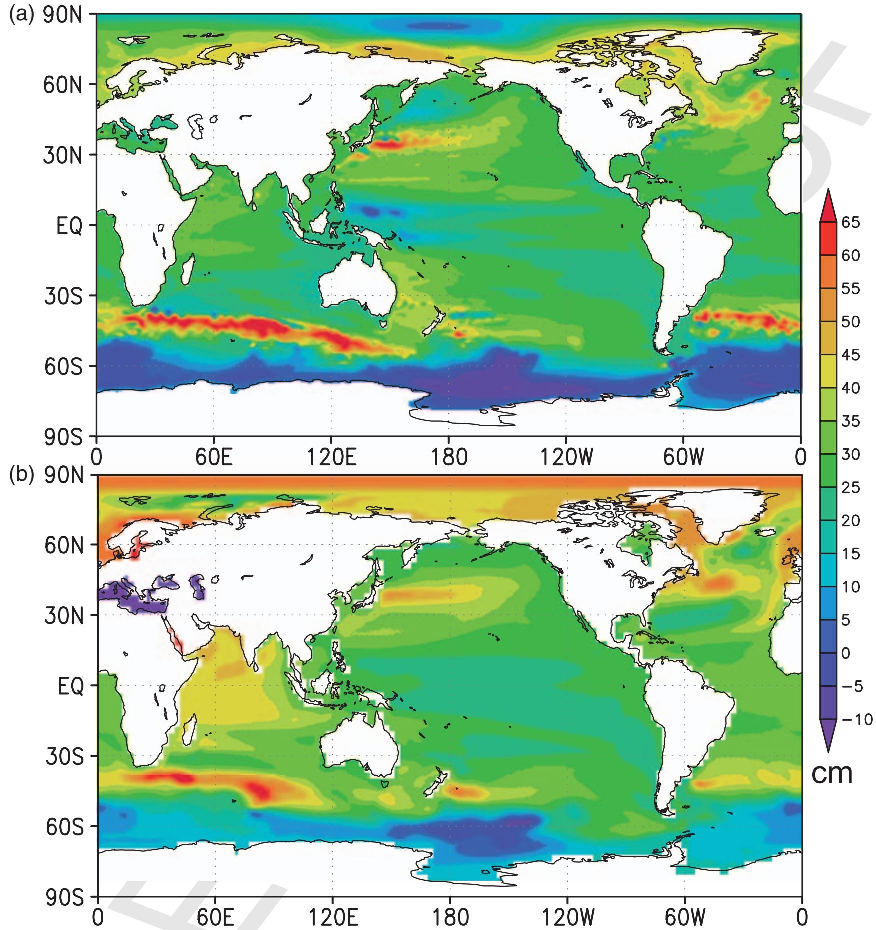

Figure 6.7 The changes in mean steric sea-surface height (2080–2100 mean minus the 1980–2000 mean) for the A1B scenario in (a) MIROC3.2_hi and (b) MIROC3.2_med (Suzuki et al. 2005). See text for abbreviations.

Ocean. Landerer et al. (2007a) found this is largely due to enhanced freshwater input from precipitation and river runoff in the northern high latitudes and a subsequent change of the density structure in this region. In the Southern Ocean, local steric sea-level rise is larger than the global average in a band running along the poleward edge of the subtropical gyre (there is a similar feature in the Northern Hemisphere) and smaller than the average south of the Antarctic Circumpolar Current. There is little improvement in agreement between models assessed in the IPCC Fourth Assessment Report (AR4) compared with the IPCC Third Assessment Report (TAR) and significant and inadequately understood differences remain between the various model projections (Pardaens et al. 2010).

6.5.3 Higher-Resolution Model Estimates of Steric Sea-Level Rise

Recent increases in computing power have enabled long-time integrations of higher-resolution climate models, thus permitting better (but not fully resolving) representation of bottom topography and ocean meso-scale structures such as western boundary currents, eddies, fronts, and deep-water formation. As a result, there is potential for improved representation of processes contributing to ocean thermosteric sea-level rise such as subduction of water masses, the large spatial-scale variability in ocean mixing, and deep-water formation.

The high-resolution version of the Model for Interdisciplinary Research on Climate version 3.2 (MIROC3.2_hi) has the highest resolution of all the models used in the AR4. This model (K-1 Model Developers 2004) consists of a T106 atmospheric spectral model (about 1.1° resolution at the equator) and an eddy-permitting ocean model with resolution of 0.28° zonally and 0.19° meridionally, and 48 vertical levels. Because of the greatly increased computing resources required, only one realization of the high-resolution model is available. The medium resolution version (MIROC3.2_med) has similar resolution to most other AR4 models.

The steric contribution during the 21st century is projected to be about 30 cm for the A1B scenario and 23 cm for the B1 scenario in the MIROC3.2_hi, similar to those for the MIROC3.2_med and within but near the top of the range of estimates from other models (Suzuki et al. 2005). However, the total heat flux into the ocean in the MIROC3.2_hi is larger than that in the MIROC3.2_med during the early 21st century and smaller after the middle of the 21st century. The upper ocean in the MIROC3.2_hi warms earlier than that in the MIROC3.2_med and the warming of the deeper ocean is smaller in the MIROC3.2_hi than in the MIROC3.2_med. These differences in ocean heat uptake may partly reflect the inability of coarse-resolution models to simulate the upper ocean stratification and the vertical distribution of ocean-heat uptake and/or the difference in strength of the meridional overturning circulation between the two models: the Atlantic meridional overturning circulation is weakened from 14 to 9 Sv in the MIROC3.2_hi and from 19.5 to 12.5 Sv in the MIROC3.2_med during the 21st century. It also may be related to the difference in climate sensitivity between the two models, with MIROC3.2_hi having a higher sensitivity than MIROC3.2_med.

The broad-scale features of regional sea-level rise of the coarse resolution models are similar in both models (Figure 6.7). However, in MIROC3.2_hi the representation of finer-scale features means the magnitudes of changes are more pronounced and more confined to specific areas than in the MIROC3.2_med and other coarse-resolution models. For example, in the Arctic Ocean enhanced sea-level rise is confined to the coastal region. In the Kuroshio Extension there is a reduced sea-level rise north of the Kuroshio at approximately 150°E and an enhanced sea-level rise to the south. This change is associated with the acceleration of the Kuroshio caused by changes in wind stress and the consequential spin-up of the Kuroshio recirculation (Sakamoto et al. 2005). In contrast, the Kuroshio in the MIROC3.2_med overshoots to the north, so the region of large sea-level rise in the MIROC3.2_med extends northward relative to that in the MIROC3.2_hi. Improving the resolution of these regional features and their representation on continental shelves and in semi-enclosed seas will be important in understanding the impacts of sea-level rise. As yet these issues have received little attention.

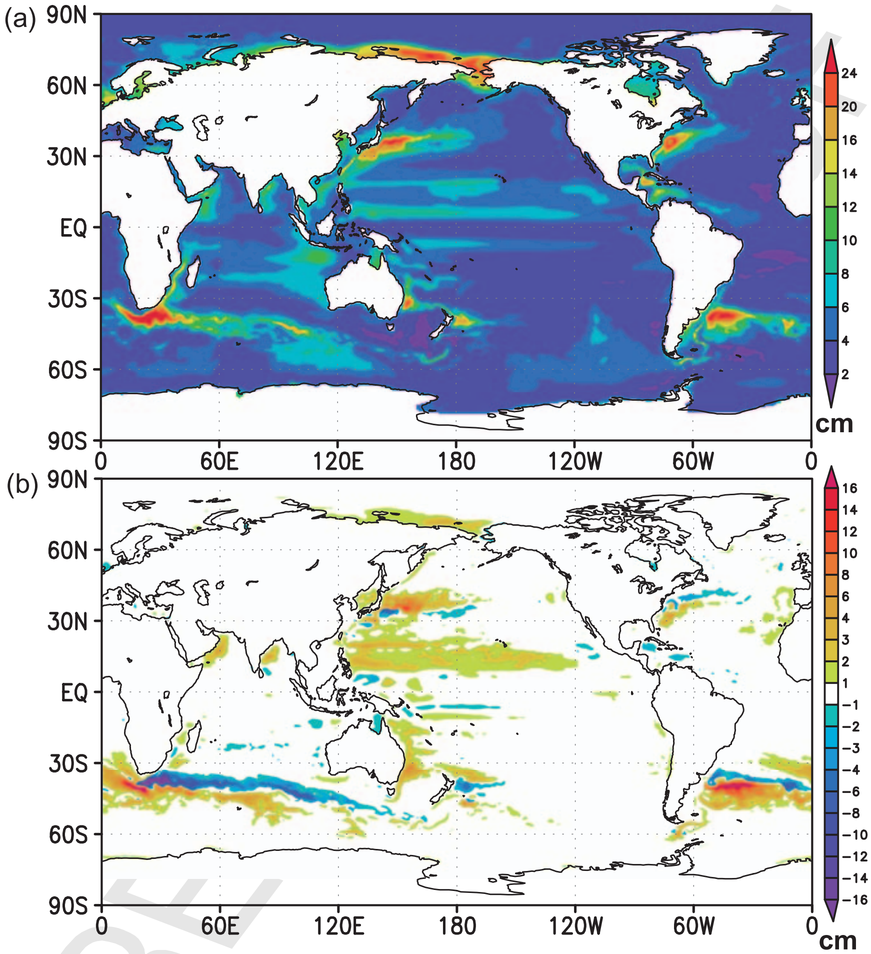

Figure 6.8 Modeled sea-surface height eddy variability. (a) The root mean square (rms) of the sea level anomaly from the 3-month running mean for the control run in MIROC3.2_hi. (b) Changes in the rms between 1980–2000 and 2080–2100 (A1B scenario) in MIROC3.2_hi (Suzuki et al. 2005).

Eddy activity is enhanced during the 21st century in MIROC3.2_hi (Figure 6.8). While the global averaged change in the rms height variability is small compared to the globally averaged rise, enhanced eddy activity is confined to specific areas, and these areas overlap with the areas of large sea-level rise around some coastal regions and islands, suggesting that both changes in mean sea level and changes in eddy variability may increase the frequency and intensity of extreme sea levels in those regions during the 21st century. An example of the impact of eddies on islands is the flooding of Okinawa Island on 22 July 2001 when a warm eddy increased sea level by more than 15 cm (Tokeshi and Yanagi 2003).

6.5.4 Ocean Processes of Sea-Level Change

Coupled AOGCMs provide the opportunity to focus on the mechanisms behind global averaged and regional sea-level changes to understand better how heat enters the ocean, to understand how it is distributed, and to understand model differences (e.g. Lowe and Gregory 2006; Landerer et al. 2007a; Levermann et al. 2005; Suzuki et al. 2005).

In a series of carbon dioxide-doubling experiments, Lowe and Gregory (2006) found global mean-sea-level rise is dominated by the thermal expansion of the ocean, with changes in the salinity distribution (e.g. from changes of the hydrological cycle) having a negligible contribution to the global mean. Interior temperature changes cannot be explained solely by passive tracer transports along isopycnals with no changes in ocean circulation (Banks and Gregory 2006). Instead, the heat is redistributed by changes in the ocean circulation, and in the deeper layers there is a significant diapycnal component (Banks and Gregory 2006). The changes in regional sea level are primarily a result of density (baroclinic) changes in the ocean rather than a change in the barotropic circulation (Lowe and Gregory 2006). Temperature change is the largest contribution to these density changes and is usually positive. However, the salinity changes also make a significant local contribution, often opposing the temperature changes (see also Landerer et al. 2007a; Figure 6.9). Changes in surface wind stress were most important for determining the regional distribution of sea-level rise but changes in surface fluxes of heat and fresh water were important regionally (Lowe and Gregory 2006) and according to Köhl and Stammer (2008) buoyancy fluxes have become increasingly important for regional changes during 1992–2001. In the high-latitude Southern Ocean, the relatively small sea-level rise was related to the small thermal expansion there. In contrast, Landerer et al. (2007a) emphasized the increased wind stress, leading to a stronger Antarctic Circumpolar Current transport and a subsequent dynamic sea-surface height adjustment in the model (Figure 6.9). However, note that recent observations suggest that the strengthened winds have not resulted in a strengthening of the Antarctic Circumpolar Current (Böning et al. 2008) and in a quasi-geostrophic model the increased winds lead to an intensification of the eddy field on interannual timescales rather than a strengthening of the current (Hogg et al. 2008).

Levermann et al. (2005) find a linear scaling of 4.5–5 cm/Sv between sea level at the North American coast and the maximum North Atlantic meridional overturning circulation. However, while Landerer et al. (2007a) show that the sea-surface height difference between Bermuda and the Labrador Sea correlates highly at zero lag with the combined interannual to decadal North Atlantic gyre transport changes, changes in the overturning circulation cannot be reliably inferred from sea-surface height. Landerer et al. (2007a) report that the basin-integrated sea-surface height difference of 0.78 m between the North Atlantic and North Pacific Ocean is reduced by only 0.06 m when the North Atlantic meridional overturning circulation is reduced by 25% in their simulation, and is re-established within 100 years through a Pacific Ocean sea-surface height rise and a North Atlantic sea-surface height drop, without an analogous recovery of the North Atlantic overturning.

The vertical distribution of thermosteric and halosteric anomalies that contribute to sea-level change is very different between ocean basins. In the North Atlantic, the steric anomalies reach to depths of the North Atlantic Deep Water

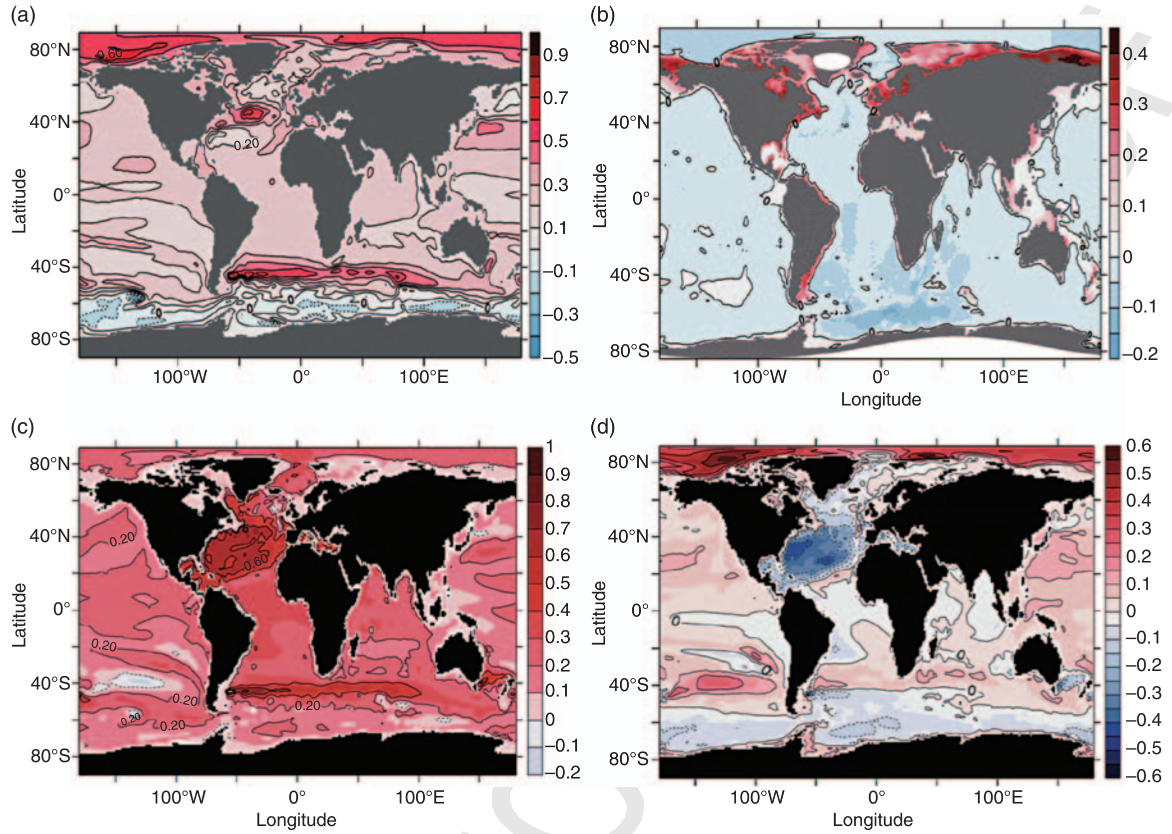

Figure 6.9 (a) Simulated sea-level changes for the period 2090–2099 relative to the pre-industrial state; (b) mass-redistribution component; (c) thermosteric contribution; and (d) halosteric contribution. No external mass source (e.g. melting glaciers) is included in the simulation (Landerer et al. 2007a, 2007b). All data are in meters. (© American Meteorological Society.)

(2000 m), whereas steric anomalies in the entire Pacific Ocean occur mainly in the upper 500 m. In the Southern Ocean, steric anomalies occur throughout the entire water column, reflecting the deep structure of the Antarctic Circumpolar Current and possibly the strong vertical exchange of buoyancy in this region (Figure 6.10; Landerer et al. 2007a). Whether or not the thermosteric and the halosteric anomalies are additive or density-compensating also varies between ocean basins and latitude bands (Levitus et al. 2005b).

Although steric sea-level changes occur at constant global ocean mass, mass redistribution within the global ocean causes bottom pressure to increase across shallow shelf areas following ocean thermal expansion (Figure 6.9). Landerer et al. (2007a, 2007b) estimate that bottom pressure increases by up to 0.4 m sea-level height equivalent in their simulation. Due to the laterally varying distribution of shelf areas, these surface mass-loading anomalies directly affect the geoid and thus

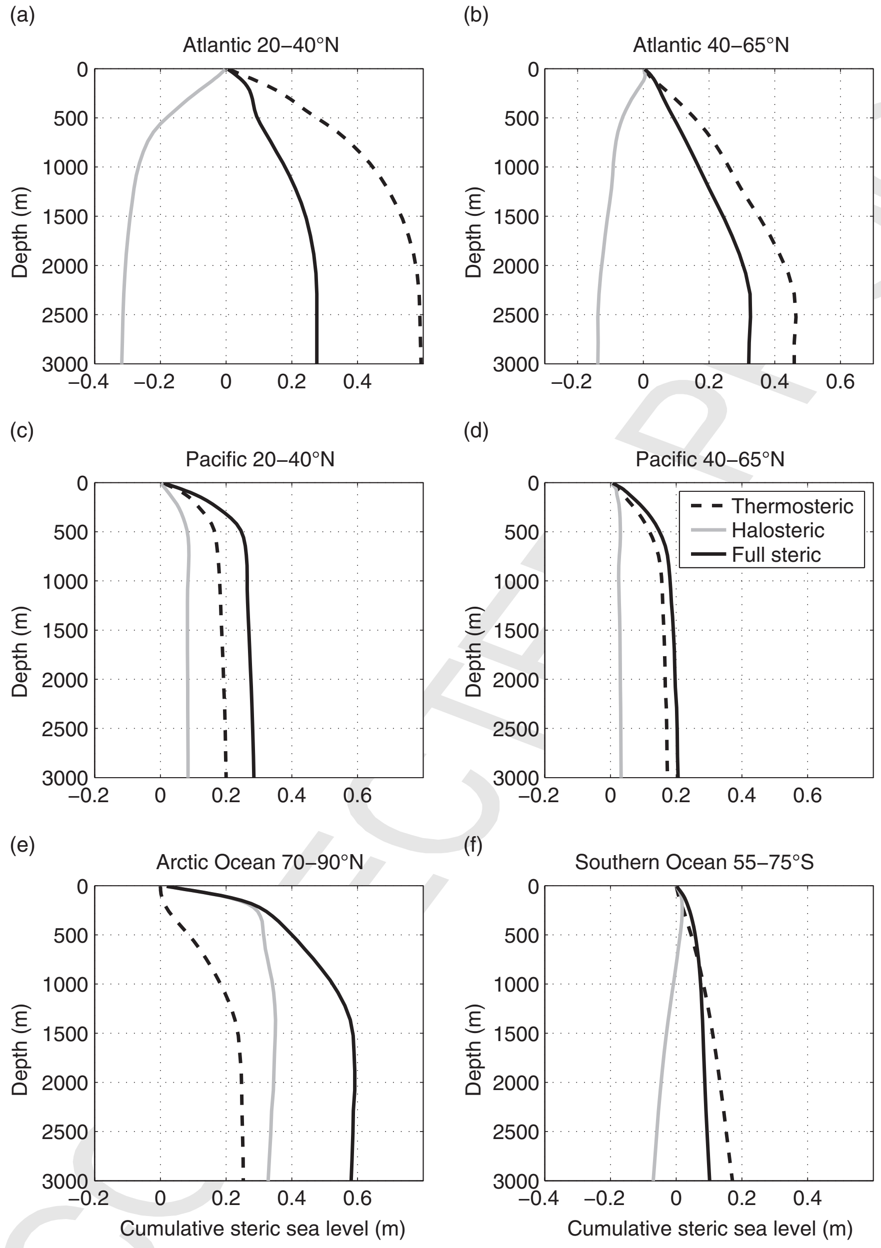

Figure 6.10 Cumulative sum of thermosteric (dashed line), halosteric (gray line), and total steric (black line) anomalies for different ocean areas. Starting at the surface, the steric anomaly from each depth layer is accumulated. Note that the abscissa has the same width in all plots (Landerer et al. 2007a). (© American Meteorological Society.)

relative sea-level rise, and also Earth orientation parameters, for example polar motion and length of day (Landerer et al. 2007b, 2009).

6.6 Conclusions and Recommendations

Significant progress has been made during the past 20 years in observing and understanding the seasonal to decadal variability and the multidecadal trends in global-ocean heat content and steric sea-level change. Adding to the historical database through data archaeology efforts has contributed enormously (Levitus et al. 2005d). However, during the 1950s and 1960s vast regions of the oceans went unsampled. Since then, greater interest in climate issues and the open ocean, and advances in measurement technology, have resulted in a tremendous evolution of the ocean-observing system. The combination of high-precision satellite altimetry and global upper-ocean observations of the Argo Project (Gould et al. 2004) means the sampling and instrumental problems of the 1950s to 1990s are now being significantly reduced for the upper-ocean heat and salt distributions.

Comparisons of different data sets and the use of different statistical approaches have helped address and partially overcome the sampling (spatial/temporal) and instrumental biases for the upper 700 m of the ocean. A recent estimate of the trend in thermosteric sea-level rise from 1961 to 2003 is larger than earlier estimates, as much as 0.52 ± 0.08 mm/year for the upper 700 m (Domingues et al. 2008). There are indications of a significant but poorly quantified deep and abyssal ocean contribution.

There has also been tremendous progress in the development of AOGCMs. The agreement between the models and observations of both the variability and trends in the upper ocean has improved (Domingues et al. 2008). However, substantial differences remain between the observations and the model estimates for the 20th century and between the various model projections for the 21st century.

There is not, as yet, convergence in assessments and projections of the regional distribution of sea-level rise (Church et al. 2004; Llovel et al. 2009; Gregory et al. 2001; Pardaens et al. 2010). An emerging issue is the importance of increased spatial resolution, including resolving continental shelves and semi-enclosed seas. The only eddy resolving model used in the last IPCC Assessment has important differences to its lower-resolution equivalent and has pointed to the potential importance of changes in the amplitude of eddy activity in some regions and its impact on ocean circulation and coastal flooding.

Our present thermosteric sea-level-observing elements of Argo for upper-ocean thermal expansion, the Jason series of high-quality satellite altimeter missions for ocean volume, and GRACE to separately observe changes in ocean mass are complementary. Argo has virtually complete coverage of the upper 1000–2000 m of the ice-free oceans. The high-quality temperature, conductivity, and pressure instruments used on Argo floats are being carefully calibrated and carry an accurate and stable thermistor. Small drifts in pressure transducers are being monitored, corrected, and reduced with improved sensors. High-quality salinity measurements are made by all floats, and in most cases are free of significant drift for 2 years or longer. Argo should ultimately (with the application of careful quality-control measures) have an error in 12-month upper-ocean global means of the order of 1 mm (Willis et al. 2004). For altimetric height, errors in multiyear global mean-sea-level trends can be as low as 0.4 mm/year (Leuliette et al. 2004). Given typical interannual variability of 1–3 mm/year for each of these quantities, the decomposition of sea level into upper-ocean steric and ocean-mass components should be adequately observed on annual, interannual, and longer timescales. Moreover, as noted above the Argo salinity measurements will provide an additional constraint on the upper ocean's freshwater budget, and consequently on ocean-mass change. Comparison of the trends of these complementary observations, as attempted by Willis et al. (2008), Cazenave et al. (2009), and Leuliette and Miller (2009), will be critically important for identifying remaining deficiencies and biases in our observation.

While significant progress has been made in observing the global oceans, clear deficiencies remain. The historical record is plagued by insufficient data, particularly in the deep and abyssal and ice-covered ocean. It is important that further efforts be made to add to the historical database through data archaeology and develop improved analysis of this data, including data assimilation. For practical reasons the Argo array is presently limited to the upper 2000 m of the oceans and to the ice-free regions, and there are relatively few floats in marginal seas. Instrument development is already mitigating these problems. Design work is needed to define the sampling requirements and techniques for observing the deep ocean. Implementation of the deep-ocean-observing system will require new resources. These deep-ocean issues are important for the very long timescales associated with steric sea-level rise and have important implications for policy decisions regarding appropriate greenhouse gas stabilization levels.

We also need to pay much greater attention to understanding the temporal and regional distribution of steric sea-level rise in both observations and models, including the presence of ocean eddies.

In addition to understanding deep-ocean steric sea-level rise and its temporal and spatial distribution, we need to understand how deep-ocean conditions impact the continental shelf and coastal sea levels. This includes both the direct effects of regional sea-level rise and also remotely forced sea-level perturbations that may be transmitted over large distances in the coastal (and equatorial) wave guides. The integrated framework for consideration of the impact of offshore phenomena on coastal sea level, including systematic observations in the coastal zone, is incomplete.

Recommendations for further observational activities and numerical model studies are:

- expand the historical database through data archaeology and improve the quality control of these data;

- sustain the Argo observational project, and extend the Argo coverage to marginal seas and ice-covered regions;
- design and implement appropriate observational strategies for the coastal region and the deep ocean (below the depth of the Argo floats);
- maintain the highest-quality satellite altimeter and time-variable gravity observations,
- improve and apply new techniques for reanalysis of the historical ocean database of 1950 to present, including statistical techniques and modern, robust data assimilation techniques;
- improve understanding, detection, and attribution of past steric sea-level rise on a range of spatial scales;
- reduce uncertainty in projections of 21st century steric sea-level rise through both model improvement and better use of observational constraints; and
- investigate high-resolution (including shelf sea/coastal) steric changes and produce better regional projections of steric sea-level change.

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