

- Research Series 74. Washington: American Geophysical Union.
- Leppäranta M (ed.) (1998) *Physics of Ice-Covered Seas*, vols 1 and 2. University of Helsinki Press.
- Wadhams P (2000) *Ice in the Ocean*. London: Gordon and Breach.
- Wadhams P, Dowdeswell JA and Schofield AN (eds) (1996) *The Arctic and Environmental Change*. London: Gordon and Breach Publishers.
- Wadhams P, Gascard J-C and Miller L (eds) (1999) The European Subpolar Ocean Programme: ESOP. *Deep-Sea Research II* 46: 1011–1530 (special issue).
- Wheeler PA (ed.) (1997) 1994 Arctic Ocean Section. *Deep-Sea Research II* 44: (Special issue)
- Zwally HJ, Comiso JC, Parkinson CL *et al.* (1983). *Antarctic Sea Ice 1973–1976: Satellite Passive Microwave Observations*. Washington, DC: NASA, Report. SP-459.

SEA LEVEL CHANGE

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doi:10.1006/rwos.2001.0268

Introduction

Sea-level changes on a wide range of time and space scales. Here we consider changes in mean sea level, that is, sea level averaged over a sufficient period of time to remove fluctuations associated with surface waves, tides, and individual storm surge events. We focus principally on changes in sea level over the last hundred years or so and on how it might change over the next one hundred years. However, to understand these changes we need to consider what has happened since the last glacial maximum 20 000 years ago. We also consider the longer-term implications of changes in the earth's climate arising from changes in atmospheric greenhouse gas concentrations.

Changes in mean sea level can be measured with respect to the nearby land (relative sea level) or a fixed reference frame. Relative sea level, which changes as either the height of the ocean surface or the height of the land changes, can be measured by a coastal tide gauge.

The world ocean, which has an average depth of about 3800 m, contains over 97% of the earth's water. The Antarctic ice sheet, the Greenland ice sheet, and the hundred thousand nonpolar glaciers/ice caps, presently contain water sufficient to raise sea level by 61 m, 7 m, and 0.5 m respectively if they were entirely melted. Ground water stored shallower than 4000 m depth is equivalent to about 25 m (12 m stored shallower than 750 m) of sea-level change. Lakes and rivers hold the equivalent of less than 1 m, while the atmosphere accounts for only about 0.04 m.

On the time-scales of millions of years, continental drift and sedimentation change the volume of the

ocean basins, and hence affect sea level. A major influence is the volume of mid-ocean ridges, which is related to the arrangement of the continental plates and the rate of sea floor spreading.

Sea level also changes when mass is exchanged between any of the terrestrial, ice, or atmospheric reservoirs and the ocean. During glacial times (ice ages), water is removed from the ocean and stored in large ice sheets in high-latitude regions. Variations in the surface loading of the earth's crust by water and ice change the shape of the earth as a result of the elastic response of the lithosphere and viscous flow of material in the earth's mantle and thus change the level of the land and relative sea level. These changes in the distribution of mass alter the gravitational field of the earth, thus changing sea level. Relative sea level can also be affected by local tectonic activities as well as by the land sinking when ground water is extracted or sedimentation increases. Sea water density is a function of temperature. As a result, sea level will change if the ocean's temperature varies (as a result of thermal expansion) without any change in mass.

Sea-Level Changes Since the Last Glacial Maximum

On timescales of thousands to hundreds of thousands of years, the most important processes affecting sea level are those associated with the growth and decay of the ice sheets through glacial-interglacial cycles. These are also relevant to current and future sea-level rise because they are the cause of ongoing land movements (as a result of changing surface loads and the resultant small changes in the shape of the earth – postglacial rebound) and ongoing changes in the ice sheets.

Sea-level variations during a glacial cycle exceed 100 m in amplitude, with rates of up to tens of millimetres per year during periods of rapid decay of the ice sheets (Figure 1). At the last glacial

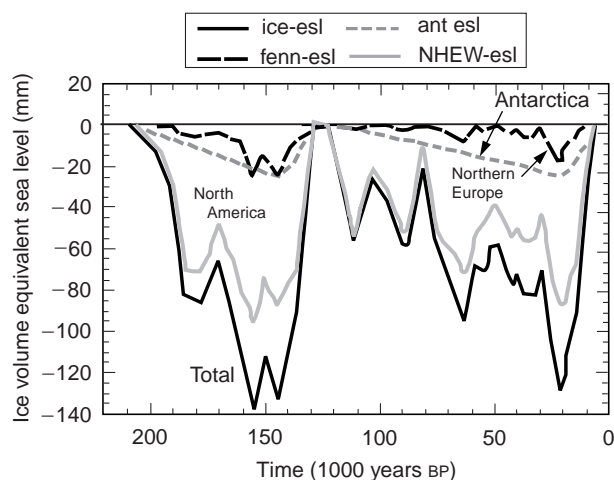


Figure 1 Change in ice sheet volume over the last 200 000 years. Fenn, Fennoscandian; ant, Antarctic; NHEW; North America; esl, equivalent sea level. (Reproduced from Lambeck, 1998.)

maximum (about 21 000 years ago), sea level was more than 120 m below current levels. The largest contribution to this sea-level lowering was the additional ice that formed the North American (Laurentide) and European (Fennoscandian) ice sheets. In addition, the Antarctic ice sheet was larger than at present and there were smaller ice sheets in presently ice-free areas.

Observed Recent Sea-Level Change

Long-term relative sea-level changes have been inferred from the geological records, such as radiocar-

bon dates of shorelines displaced from present day sea level, and information from corals and sediment cores. Today, the most common method of measuring sea level relative to a local datum is by tide gauges at coastal and island sites. A global data set is maintained by the Permanent Service for Mean Sea Level (PSMSL). During the 1990s, sea level has been measured globally with satellites.

Tide-gauge Observations

Unfortunately, determination of global-averaged sea-level rise is severely limited by the small number of gauges (mostly in Europe and North America) with long records (up to several hundred years, **Figure 2**). To correct for vertical land motions, some sea-level change estimates have used geological data, whereas others have used rates of present-day vertical land movement calculated from models of postglacial rebound.

A widely accepted estimate of the current rate of global-average sea-level rise is about 1.8 mm y^{-1} . This estimate is based on a set of 24 long tide-gauge records, corrected for land movements resulting from deglaciation. However, other analyses produce different results. For example, recent analyses suggest that sea-level change in the British Isles, the North Sea region and Fennoscandia has been about 1 mm y^{-1} during the past century. The various assessments of the global-average rate of sea-level change over the past century are not all consistent within stated uncertainties, indicating further sources of error. The treatment of vertical land movements remains a source of potential inconsistency, perhaps amounting to 0.5 mm y^{-1} . Other sources of

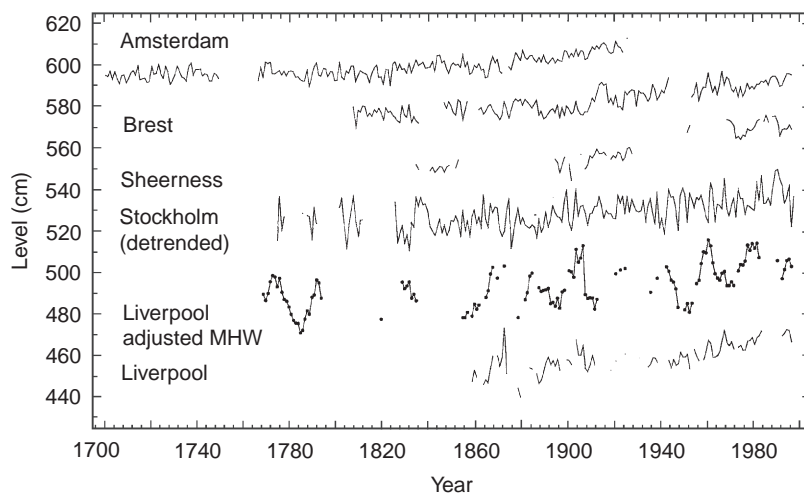


Figure 2 Time series of relative sea level over the last 300 years from several European coastal locations. For the Stockholm record, the trend over the period 1774 to 1873 has been removed from the entire data set. For Liverpool two series are given. These are the mean sea level and, for a longer period, the mean high water (MHW) level. (Reproduced with permission from Woodworth, 1999.)

error include variability over periods of years and longer and any spatial distribution in regional sea level rise (perhaps several tenths of a millimeter per year).

Comparison of the rates of sea-level rise over the last 100 years ($1.0\text{--}2.0\text{ mm y}^{-1}$) and over the last two millennia ($0.1\text{--}0.2\text{ mm y}^{-1}$) suggests the rate has accelerated fairly recently. From the few very long tide-gauge records (Figure 2), it appears that an acceleration of about $0.3\text{--}0.9\text{ mm y}^{-1}$ per century occurred over the nineteenth and twentieth century. However, there is little indication that sea-level rise accelerated during the twentieth century.

Altimeter Observations

Following the advent of high-quality satellite radar altimeter missions in the 1990s, near-global and homogeneous measurement of sea level is possible, thereby overcoming the inhomogeneous spatial sampling from coastal and island tide gauges. However, clarifying rates of global sea-level change requires continuous satellite operations over many years and careful control of biases within and between missions.

To date, the TOPEX/POSEIDON satellite-altimeter mission, with its (near) global coverage from 66°N to 66°S (almost all of the ice-free oceans) from late 1992 to the present, has proved to be of most value in producing direct estimates of sea-level change. The present data allow global-average sea level to be estimated to a precision of several millimeters every 10 days, with the absolute accuracy limited by systematic errors. The most recent estimates of global-average sea level rise based on the short (since 1992) TOPEX/POSEIDON time series range from 2.1 mm y^{-1} to 3.1 mm y^{-1} .

The altimeter record for the 1990s indicates a rate of sea-level rise above the average for the twentieth century. It is not yet clear if this is a result of an increase in the rate of sea-level rise, systematic differences between the tide-gauge and altimeter data sets or the shortness of the record.

Processes Determining Present Rates of Sea-Level Change

The major factors determining sea-level change during the twentieth and twenty-first century are ocean thermal expansion, the melting of nonpolar glaciers and ice caps, variation in the mass of the Antarctic and Greenland ice sheets, and changes in terrestrial storage.

Projections of climate change caused by human activity rely principally on detailed computer models referred to as atmosphere–ocean general circula-

tion models (AOGCMs). These simulate the global three-dimensional behavior of the ocean and atmosphere by numerical solution of equations representing the underlying physics. For simulations of the next hundred years, future atmospheric concentrations of gases that may affect the climate (especially carbon dioxide from combustion of fossil fuels) are estimated on the basis of assumptions about future population growth, economic growth, and technological change. AOGCM experiments indicate that the global-average temperature may rise by $1.4\text{--}5.8^\circ\text{C}$ between 1990 and 2100, but there is a great deal of regional and seasonal variation in the predicted changes in temperature, sea level, precipitation, winds, and other parameters.

Ocean Thermal Expansion

The broad pattern of sea level is maintained by surface winds, air–sea fluxes of heat and fresh water (precipitation, evaporation, and fresh water runoff from the land), and internal ocean dynamics. Mean sea level varies on seasonal and longer timescales. A particularly striking example of local sea-level variations occurs in the Pacific Ocean during El Niño events. When the trade winds abate, warm water moves eastward along the equator, rapidly raising sea level in the east and lowering it in the west by about 20 cm.

As the ocean warms, its density decreases. Thus, even at constant mass, the volume of the ocean increases. This thermal expansion is larger at higher temperatures and is one of the main contributors to recent and future sea-level change. Salinity changes within the ocean also have a significant impact on the local density, and thus on local sea level, but have little effect on the global-average sea level.

The rate of global temperature rise depends strongly on the rate at which heat is moved from the ocean surface layers into the deep ocean; if the ocean absorbs heat more readily, climate change is retarded but sea level rises more rapidly. Therefore, time-dependent climate change simulation requires a model that represents the sequestration of heat in the ocean and the evolution of temperature as a function of depth. The large heat capacity of the ocean means that there will be considerable delay before the full effects of surface warming are felt throughout the depth of the ocean. As a result, the ocean will not be in equilibrium and global-average sea level will continue to rise for centuries after atmospheric greenhouse gas concentrations have stabilized. The geographical distribution of sea-level change may take many decades to arrive at its final state.

While the evidence is still somewhat fragmentary, and in some cases contradictory, observations indicate ocean warming and thus thermal expansion, particularly in the subtropical gyres, at rates resulting in sea-level rise of order 1 mm y^{-1} . The observations are mostly over the last few decades, but some observations date back to early in the twentieth century. The evidence is most convincing for the subtropical gyre of the North Atlantic, for which the longest temperature records (up to 73 years) and most complete oceanographic data sets exist. However, the pattern also extends into the South Atlantic and the Pacific and Indian oceans. The only areas of substantial ocean cooling are the subpolar gyres of the North Atlantic and perhaps the North Pacific. To date, the only estimate of a global average rate of sea-level rise from thermal expansion is 0.55 mm y^{-1} .

The warming in the Pacific and Indian Oceans is confined to the main thermocline (mostly the upper 1 km) of the subtropical gyres. This contrasts with the North Atlantic, where the warming is also seen at greater depths.

AOGCM simulations of sea level suggest that during the twentieth century the average rate of change due to thermal expansion was of the order of $0.3\text{--}0.8 \text{ mm y}^{-1}$ (Figure 3). The rate rises to $0.6\text{--}1.1 \text{ mm y}^{-1}$ in recent decades, similar to the observational estimates of ocean thermal expansion.

Nonpolar Glaciers and Ice Caps

Nonpolar glaciers and ice caps are rather sensitive to climate change, and rapid changes in their mass contribute significantly to sea-level change. Glaciers gain mass by accumulating snow, and lose mass (ablation) by melting at the surface or base. Net accumulation occurs at higher altitude, net ablation at lower altitude. Ice may also be removed by discharge into a floating ice shelf and/or by direct calving of icebergs into the sea.

In the past decade, estimates of the regional totals of the area and volume of glaciers have been improved. However, there are continuous mass balance records longer than 20 years for only about 40 glaciers worldwide. Owing to the paucity of measurements, the changes in mass balance are estimated as a function of climate.

On the global average, increased precipitation during the twenty-first century is estimated to offset only 5% of the increased ablation resulting from warmer temperatures, although it might be significant in particular localities. (For instance, while glaciers in most parts of the world have had negative mass balance in the past 20 years, southern Scandinavian glaciers have been advancing, largely because of increases in precipitation.) A detailed computa-

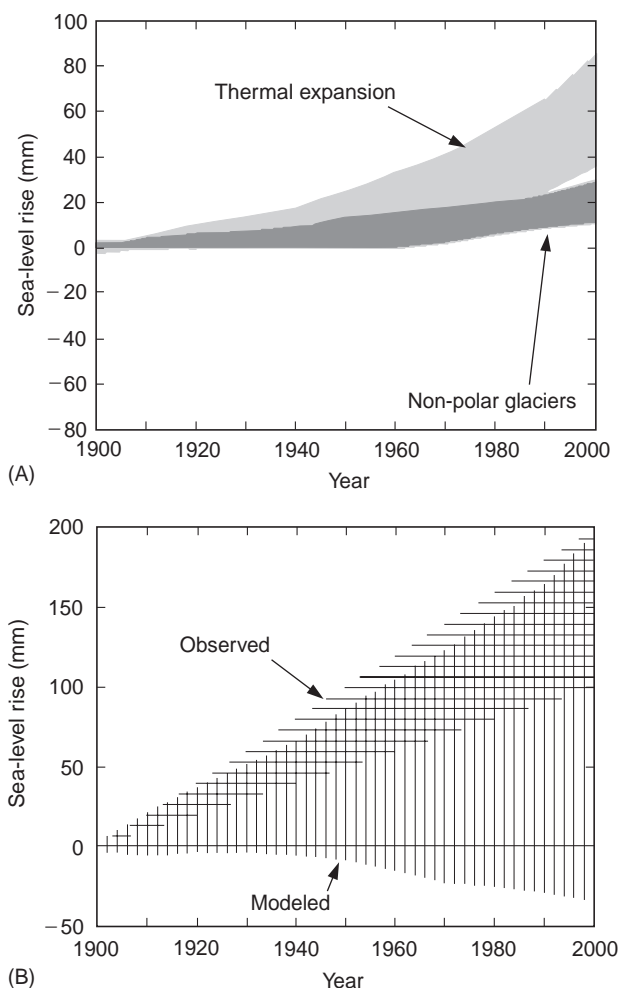


Figure 3 Computed sea-level rise from 1900 to 2000 AD. (A) The estimated thermal expansion is shown by the light stippling; the estimated nonpolar glacial contribution is shown by the medium-density stippling. (B) The computed total sea level change during the twentieth century is shown by the vertical hatching and the observed sea-level change is shown by the horizontal hatching.

tion of transient response also requires allowance for the contracting area of glaciers.

Recent estimates of glacier mass balance, based on both observations and model studies, indicate a contribution to global-average sea level of 0.2 to 0.4 mm y^{-1} during the twentieth century. The model results shown in Figure 3 indicate an average rate of 0.1 to 0.3 mm y^{-1} .

Greenland and Antarctic Ice Sheets

A small fractional change in the volume of the Greenland and Antarctic ice sheets would have a significant effect on sea level. The average annual solid precipitation falling onto the ice sheets is equivalent to 6.5 mm of sea level, but this input is approximately balanced by loss from melting and

iceberg calving. In the Antarctic, temperatures are so low that surface melting is negligible, and the ice sheet loses mass mainly by ice discharge into floating ice shelves, which melt at their underside and eventually break up to form icebergs. In Greenland, summer temperatures are high enough to cause widespread surface melting, which accounts for about half of the ice loss, the remainder being discharged as icebergs or into small ice shelves.

The surface mass balance plays the dominant role in sea-level changes on a century timescale, because changes in ice discharge generally involve response times of the order of 10^2 to 10^4 years. In view of these long timescales, it is unlikely that the ice sheets have completely adjusted to the transition from the previous glacial conditions. Their present contribution to sea-level change may therefore include a term related to this ongoing adjustment, in addition to the effects of climate change over the last hundred years. The current rate of change of volume of the polar ice sheets can be assessed by estimating the individual mass balance terms or by monitoring surface elevation changes directly (such as by airborne and satellite altimetry during the 1990s). However, these techniques give results with large uncertainties. Indirect methods (including numerical modeling of ice-sheets, observed sea-level changes over the last few millennia, and changes in the earth's rotation parameters) give narrower bounds, suggesting that the present contribution of the ice sheets to sea level is a few tenths of a millimeter per year at most.

Calculations suggest that, over the next hundred years, surface melting is likely to remain negligible in Antarctica. However, projected increases in precipitation would result in a net negative sea-level contribution from the Antarctic ice sheet. On the other hand, in Greenland, surface melting is projected to increase at a rate more than enough to offset changes in precipitation, resulting in a positive contribution to sea-level rise.

Changes in Terrestrial Storage

Changes in terrestrial storage include reductions in the volumes of some of the world's lakes (e.g., the Caspian and Aral seas), ground water extraction in excess of natural recharge, more water being impounded in reservoirs (with some seeping into aquifers), and possibly changes in surface runoff. Order-of-magnitude evaluations of these terms are uncertain but suggest that each of the contributions could be several tenths of millimeter per year, with a small net effect (Figure 3). If dam building continues at the same rate as in the last 50 years of the

twentieth century, there may be a tendency to reduce sea-level rise. Changes in volumes of lakes and rivers will make only a negligible contribution.

Permafrost currently occupies about 25% of land area in the northern hemisphere. Climate warming leads to some thawing of permafrost, with partial runoff into the ocean. The contribution to sea level in the twentieth century is probably less than 5 mm.

Projected Sea-Level Changes for the Twenty-first Century

Detailed projections of changes in sea level derived from AOCGM results are given in material listed as Further Reading. The major components are thermal expansion of the ocean (a few tens of centimeters), melting of nonpolar glaciers (about 10–20 cm), melting of Greenland ice sheet (several centimeters), and increased storage in the Antarctic (several centimeters).

After allowance for the continuing changes in the ice sheets since the last glacial maximum and the melting of permafrost (but not including changes in terrestrial storage), total projected sea-level rise during the twenty-first century is currently estimated to be between about 9 and 88 cm (Figure 4).

Regional Sea-Level Change

Estimates of the regional distribution of sea-level rise are available from several AOGCMs. Our confidence in these distributions is low because there is little similarity between model results. However, models agree on the qualitative conclusion that the range of regional variation is substantial compared with the global-average sea-level rise. One common

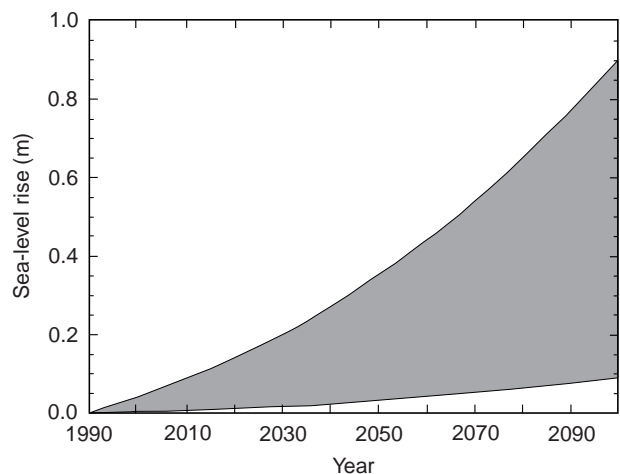


Figure 4 The estimated range of future global-average sea-level rise from 1990 to 2100 AD for a range of plausible projections in atmospheric greenhouse gas concentrations.

feature is that nearly all models predict less than average sea-level rise in the Southern Ocean.

The most serious impacts of sea-level change on coastal communities and ecosystems will occur during the exceptionally high water levels known as storm surges produced by low air pressure or driving winds. As well as changing mean sea level, climate change could also affect the frequency and severity of these meteorological conditions, making storm surges more or less severe at particular locations.

Longer-term Changes

Even if greenhouse gas concentrations were to be stabilized, sea level would continue to rise for several hundred years. After 500 years, sea-level rise from thermal expansion could be about 0.3–2 m but may be only half of its eventual level. Glaciers presently contain the equivalent of 0.5 m of sea level. If the CO₂ levels projected for 2100 AD were sustained, there would be further reductions in glacier mass.

Ice sheets will continue to react to climatic change during the present millennium. The Greenland ice sheet is particularly vulnerable. Some models suggest that with a warming of several degrees no ice sheet could be sustained on Greenland. Complete melting of the ice sheet would take at least a thousand years and probably longer.

Most of the ice in Antarctica forms the East Antarctic Ice Sheet, which would disintegrate only if extreme warming took place, beyond what is currently thought possible. The West Antarctic Ice Sheet (WAIS) has attracted special attention because it contains enough ice to raise sea level by 6 m and because of suggestions that instabilities associated with its being grounded below sea level may result in rapid ice discharge when the surrounding ice shelves are weakened. However, there is now general agreement that major loss of grounded ice, and accelerated sea-level rise, is very unlikely during the twenty-first century. The contribution of this ice sheet to sea level change will probably not exceed 3 m over the next millennium.

Summary

On timescales of decades to tens of thousands of years, sea-level change results from exchanges of mass between the polar ice sheets, the nonpolar glaciers, terrestrial water storage, and the ocean. Sea level also changes if the density of the ocean changes (as a result of changing temperature) even though there is no change in mass. During the last century, sea level is estimated to have risen by 10–20 cm, as

a result of combination of thermal expansion of the ocean as its temperature rose and increased mass of the ocean from melting glaciers and ice sheets. Over the twenty-first century, sea level is expected to rise as a result of anthropogenic climate change. The main contributors to this rise are expected to be thermal expansion of the ocean and the partial melting of nonpolar glaciers and the Greenland ice sheet. Increased precipitation in Antarctica is expected to offset some of the rise from other contributions. Changes in terrestrial storage are uncertain but may also partially offset rises from other contributions. After allowance for the continuing changes in the ice sheets since the last glacial maximum, the total projected sea-level rise over the twenty-first century is currently estimated to be between about 9 and 88 cm.

See also

Abrupt Climate Change. Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). El Niño Southern Oscillation (ENSO) Models. Forward Problem in Numerical Models. Glacial Crustal Rebound, Sea levels and Shorelines. Ice-shelf Stability. Icebergs. International Organizations. Ocean Circulation. Ocean Subduction. Past Climate From Corals. Satellite Altimetry. Sea Level Variations Over Geologic Time.

Further Reading

- Church JA, Gregory JM, Huybrechts P *et al.* (2001) Changes in sea level. In: Houghton JT (ed.) *Climate Change 2001; The Scientific Basis*. Cambridge: Cambridge University Press.
- Douglas BC, Keaney M and Leatherman SP (eds) (2000) *Sea Level Rise: History and Consequences*, 232 pp. San Diego: Academic Press.
- Fleming K, Johnston P, Zwartz D *et al.* (1998) Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters* 163: 327–342.
- Lambeck K (1998) Northern European Stage 3 ice sheet and shoreline reconstructions: Preliminary results. News 5, Stage 3 Project, Godwin Institute for Quaternary Research, 9 pp.
- Peltier WR (1998) Postglacial variations in the level of the sea: implications for climate dynamics and solid-earth geophysics. *Review of Geophysics* 36: 603–689.
- Summerfield MA (1991) *Global Geomorphology*. Harlowe: Longman.
- Warrick RA, Barrow EM and Wigley TML (1993) *Climate and Sea Level Change: Observations, Projections and Implications*. Cambridge: Cambridge University Press.
- WWW Pages of the Permanent Service for Mean Sea Level, <http://www.pol.ac.uk/psmsl/>