# 9

# Sea Level Rise

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# CONTENTS

# EXECUTIVE SUMMARY

This Section addresses three questions

- Has global-mean sea level been rising during the last 100 years?
- What are the causal factors that could explain a past rise in sea level?
- And what increases in sea level can be expected in the future?

Despite numerous problems associated with estimates of globally coherent, secular changes in sea level based on tide gauge records, we conclude that it is highly likely that sea level has been rising over the last 100 years There is no new evidence that would alter substantially the conclusions of earlier assessments regarding the rate of change Our judgement is that

- The average rate of rise over the last 100 years has been 1 0 2 0 mm $yr^{-1}$
- There is no firm evidence of accelerations in sea level rise during this century (although there is some evidence that sea level rose faster in this century compared to the previous two centuries)

As to the possible causes and their specific contributions to past sea level rise, the uncertainties are very large, particularly for Antarctica However in general it appears that the observed rise can be explained by thermal expansion of the oceans and by the increased melting of mountain glaciers and the margin of the Greenland ice sheet From present data it is impossible to judge whether the Antarctic ice sheet as a whole is currently out of balance and is contributing, either positively or negatively, to changes in sea level

Future changes in sea level were estimated for each of the IPCC forcing scenarios (using the same simple box model as in Section 6) For each scenario, three projections - best estimate, high and low - were made corresponding to the estimated range of uncertainty in each of the potential contributing factors It is found that

- For the IPCC Business-as Usual Scenario at year 2030 global-mean sea level is 8 29 cm higher than today, with a best-estimate of 18 cm At the year 2070, the rise is 21 - 71 cm, with a best-estimate of 44 cm
- Most of the contribution is estimated to derive from thermal expansion of the oceans and the increased melting of mountain glaciers and small ice caps
- On the decadal time scale, the role of the polar ice sheets is expected to be minor, but they contribute substantially to the total uncertainty Antarctica is expected to contribute negatively to sea level due to increased snow accumulation associated with warming A rapid disintegration of the West Antarctic Ice Sheet due to global warming is unlikely within the next century
- For the lower forcing scenarios (B,C and D) the sets of sea level rise projections are similar, at least until the mid 21st century On average these projections are approximately one third lower than those of the Business as Usual Scenario

Even with substantial decreases in the emissions of the major greenhouse gases, future increases in temperature and consequently, sea level are unavoidable - a sea level rise commitment - due to lags in the climate system

This present assessment does not foresee a sea level rise of ≥1 metre during the next century Nonetheless, the implied rate of rise for the best-estimate projection corresponding to the IPCC Business-as-Usual Scenario is about 3-6 times faster than over the last 100 years

## 9.1 Sea Level Rise: Introduction

This section is primarily concerned with decade-to-century changes in global-mean sea level, particularly as related to climatic change First, the evidence for sea level rise during the last 100 years is reviewed as a basis for looking for climate-sea level connections on a decade-to-century timescale Next, the possible contributing factors - thermal expansion of the oceans and the melting of land ice - to both past and future sea level change are examined Finally, the issue of future sea level due to global warming is addressed

## 9.2 Factors Affecting Sea Level

Changes in sea level occur for many reasons on different time and space scales Tide gauges measure sea level variations in relation to a fixed benchmark and thus record "relative sea level" change due both to vertical land movements and to real (eustatic) changes in the ocean level Vertical land movements result from various natural isostatic movements, sedimentation, tectonic processes and even anthropogenic activities (e g , groundwater and oil extraction) In parts of Scandinavia, for instance, relative sea level is decreasing by as much as 1m per century due to isostatic "rebound" following the last major glaciation In attempting to identify a globally-coherent, secular trend in MSL, the vertical land movements contaminate tide gauge records and have to be removed

Eustatic sea level is also affected by many factors Differences in atmospheric pressure, winds, ocean currents and density of seawater all cause spatial and temporal variations in sea level in relation to the geoid (the surface of constant gravitational potential corresponding to the surface which the ocean would assume if ocean temperature and salinity were everywhere 0°C and 35 o/oo, respectively, and surface air pressure was everywhere constant) Changes in the geoid itself, due to re-distribution of mass within the Earth, are irrelevant on the decadal-century timescales under consideration Over these timescales, the most important climate-related factors are likely to be thermal expansion of the oceans and melting of land ice (but not floating ice shelves or sea ice)

## 9.3 Has Sea Level Been Rising Over the Last 100 Years?

It is highly likely that global-mean sea level (MSL) has been rising This is the general conclusion of no fewer than 13 studies of MSL change over various periods during the last 100 years (Table 9 1) The estimates range from about 0 5mm/yr to 3 0mm/yr, with most lying in the range 1 0-2 0mm/yr

***Table 9.1:*** *Estimate of Global Sea-Level Change (updated from Barnett, 1985, Robin, 1986)*

| Rate (mm/yr) | Comments | References |
|---|---|---|
| >0 5 | Cryologic estimate | Thorarinsson (1940) † |
| 1 1 ± 0 8 | Many stations, 1807-1939 | Gutenburg (1941) |
| 1 2 - 1 4 | Combined methods | Kuenen (1950) |
| 1 1 ± 0 4 | Six stations, 1807 1943 | Lisitzin (1958, in Lisitzin 1974) |
| 1 2 | Selected stations, 1900 1950 | Fairbridge & Krebs (1962) |
| 3 0 | Many stations, 1935 1975 | Emery et al (1980) |
| 1 2 | Many stations -> regions 1880 1980 | Gornitz et al (1982) |
| 1 5 | Many stations, 1900 1975 | Klige (1982) |
| 1 5 ± 0 15 † | Selected stations, 1903-1969 | Barnett (1983) |
| 1 4 ± 0 14 † | Many stations -> regions, 1881-1980 | Barnett (1984) |
| 2 3 ± 0 23 † | Many stations -> regions, 1930 1980 | Barnett (1984) |
| 1 2 ± 0 3 † | 130 stations, 1880-1982 | Gornitz & Lebedeff (1987) |
| 1 0 ± 0 1 † | 130 stations >11 regions, 1880-1982 | Gornitz & Lebedeff (1987) |
| 1 15 | 155 stations, 1880-1986 | Barnett (1988) |
| 2 4 ± 0 9 § | 40 stations, 1920-1970 | Peltier & Tushingham (1989, 1990) |
| 1 7 ± 0 13 § | 84 stations 1900 1980 | Trupin and Wahr (1990) |

† = Value plus 95% confidence interval

§ = Mean and standard deviation

In addition, several assessments of the likely rate of past sea level rise have been made: 12±5cm since 1900 from the SCOPE 29 assessment (Bolin et al., 1986); 10-25cm since 1900 from the US DOE assessment (MacCracken and Luther, 1985), and 10-20cm over last 100 years from the PRB assessment (Polar Research Board, 1985). These assessments also include detailed reviews of the literature (Barnett, 1985, Aubrey, 1985, Robin, 1986). Rather than repeat these, we shall focus on the most recent studies and ask whether they provide any new information that would substantially alter previous assessments.

### *9.3.1 Comparison of Recent Estimates*

The analyses by Gornitz and Lebedeff (1987, also see Gornitz, 1990) used tide-gauge data from 130 stations with minimum record length of 20 years to estimate the average rate of sea level change over the period 1880-1982. This analysis differed from previous analyses (Gornitz et al., 1982) by including a more careful correction for vertical land movements using extensive data from $^{14}C$ dated Holocene sea level indicators (see below). This correction significantly reduced the spread of the trend estimates from the individual stations (Figure 9.1).

Using two different averaging techniques to produce composite global MSL curves (averaging individual stations versus regional trends), the study obtained estimates of 1.2 ± 0.3mm/yr and 1.0 ± 0.1mm/yr respectively. These results do not differ significantly from their previous findings.

The study by Barnett (1988) is an update of previous work (Barnett, 1983, 1984) in which 155 stations are analysed over the period 1880-1986. A rate of 1.15mm/yr is obtained, in close agreement with the rates noted above. However, from a comparison of the composite global sea

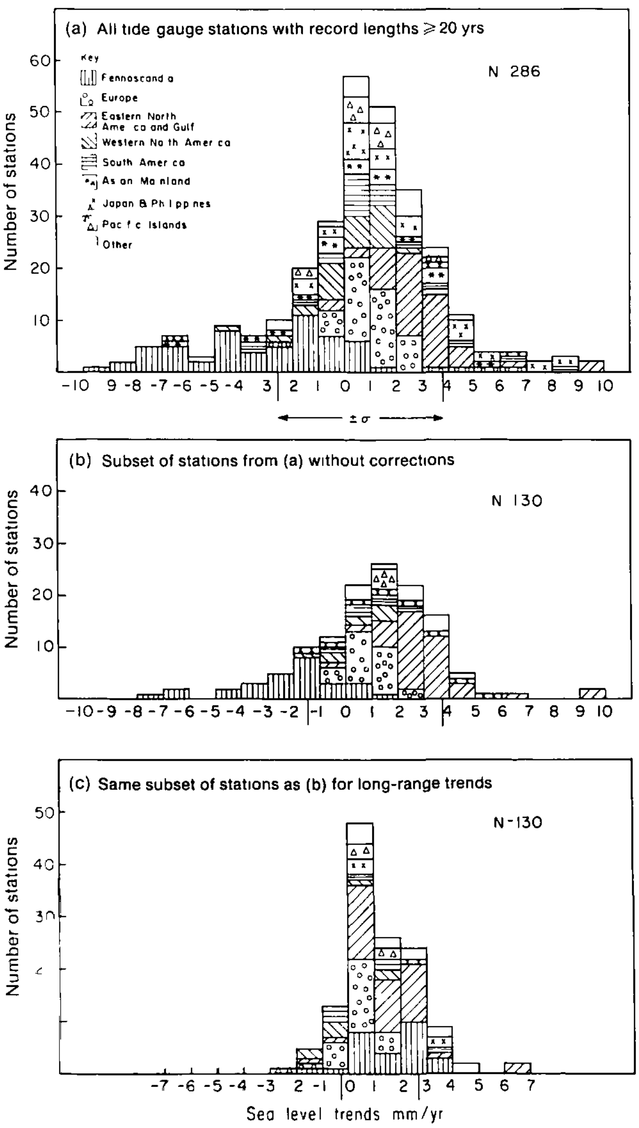


**Figure 9.1:** Histogram of number of tide-gauge stations vs sea level trends. Triangle indicates mean rate of sea-level rise; lines indicate +/- sigma. **(a)** All tide gauge stations with record length > 20 years, raw data. **(b)** Subset of tide gauge stations, long range trends included. **(c)** Same subset of stations as (a), long range trends subtracted. From Gornitz (1990).

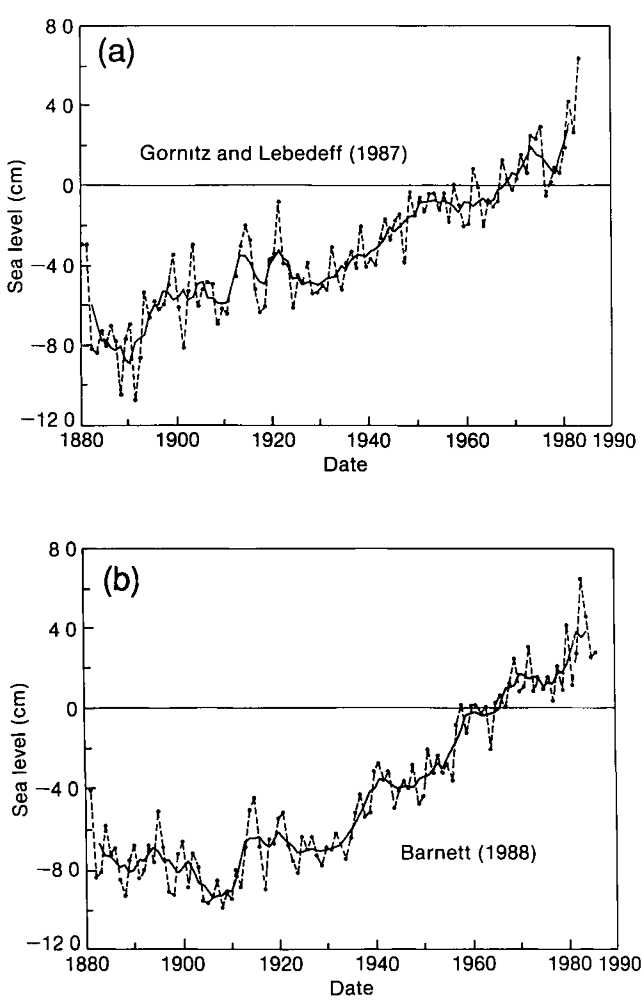


**Figure 9.2:** Global mean sea level rise over the last century. The baseline is obtained by setting the average for the period 1951-1970 to zero. The dashed line represents the annual mean and the solid line the 5 year running mean. **(a)** Gornitz and Lebedeff (1987). **(b)** Barnett (1988).

***Table 9.2*** *Time-dependency of the Tide Gauge Records (Modified from Peltier & Tushingham 1990)*

| Window Width (yr) | Start Year | End Year | No. of Records Available | LR Est. of SL Rise (mm/yr) | SD of LR Estimate (mm/yr) | EOF Est. of SL Rise (mm/yr) | SD of EOF Est. (mm/yr) |
|---|---|---|---|---|---|---|---|
| Fixed Window Width | | | | | | | |
| 51 | 1890 | 1940 | 11 | 1.6 | 1.5 | 0.7 | 0.7 |
| 51 | 1900 | 1950 | 20 | 1.6 | 0.9 | 1.2 | 0.6 |
| 51 | 1910 | 1960 | 27 | 1.8 | 0.8 | 1.4 | 0.6 |
| 51 | 1920 | 1970 | 40 | 2.3 | 0.8 | 2.4 | 0.9 |
| 51 | 1930 | 1980 | 33 | 2.0 | 1.1 | 1.5 | 0.6 |
| Variable Window Width | | | | | | | |
| 71 | 1900 | 1970 | 13 | 1.9 | 0.8 | 1.2 | 0.5 |
| 66 | 1905 | 1970 | 17 | 1.9 | 0.8 | 1.2 | 0.5 |
| 61 | 1910 | 1970 | 24 | 1.9 | 0.8 | 1.5 | 0.6 |
| 56 | 1915 | 1970 | 29 | 2.1 | 0.8 | 1.7 | 0.7 |
| 51 | 1920 | 1970 | 40 | 2.3 | 0.8 | 2.4 | 0.9 |
| 46 | 1925 | 1970 | 52 | 2.2 | 1.0 | 2.3 | 1.1 |
| 41 | 1930 | 1970 | 66 | 1.9 | 1.1 | 1.9 | 1.1 |
| 36 | 1935 | 1970 | 82 | 1.6 | 1.5 | 1.4 | 1.0 |

All tide gauge records have been reduced using the standard model

level curves (Figure 9.2), it is apparent that while Gornitz and Lebedeff's curve appears linear over the entire time period, Barnett's curve suggests a steeper rate of rise over about 1910-1980 - approximately 1.7mm/yr. This is more nearly in line with estimates of Peltier and Tushingham (1990) for the same time period (see Table 9.2).

Peltier and Tushingham (1989, 1990) select a minimum record length of 51 years, correct the data for ongoing glacial isostatic adjustments using a geophysical model, and analyse the corrected data using both linear regression (LR) techniques and empirical orthogonal function (EOF) analyses. From a final total of 40 stations over the time period 1920-1970, they conclude that the global rate of sea level rise is 2.4 ± 0.9mm/yr. This rate is considerably higher than most other estimates noted in Table 9.1. However, the authors caution that the results are sensitive to variations in the analysis procedure. As shown in Table 9.2, variations in either the record length or period of record have large effects on the estimated rate of rise. In fact, for all combinations other than their preferred period 1920-1970 (chosen to maximize the number of stations with a minimum 50-year record length), the estimated rates are lower and, in a number of cases, compare favourably with those of Gornitz and Lebedeff (1987), Barnett (1988) and Trupin and Wahr (1990).

Why the differences? Possible reasons have to do with choice of minimum record length, period of record, number of stations, geographical representation, correction procedures for vertical land movements, and methods of data aggregation and analysis. Unfortunately, these factors are interrelated and not easily isolated from published studies. Nevertheless, it is significant that, despite the differences, both the recent and earlier studies all find a positive trend in global MSL. This seems to be a rather robust finding. There is, however, the possibility that all the studies could be systematically biased.

### *9.3.2 Possible Sources of Error*

There are several potential sources of systematic bias common to all such studies. Firstly, they make use of the same global MSL dataset, that of the Permanent Service for Mean Sea Level (PSMSL), an International Council of Scientific Unions databank located at the Bidston Observatory, U.K. (Pugh et al. 1987). The PSMSL collects data from approximately 1300 stations worldwide. However, only 850 of these are suitable for time series work (the PSMSL 'Revised Local Reference' (RLR) dataset) and 420 of these are 20 years or more in length. Tide gauge records contain many signals other than a secular trend. These stem primarily from large interannual meteorological and oceanographic forcings on sea level and, in principle, can be modelled and thereby removed from the record In practice, the variability is such that accurate trends can be computed only given 15 20 years of data, which significantly reduces the size of the dataset available for analysis

Secondly, there is an historical geographical bias in the dataset in favour of Northern Europe, North America and Japan Areas of Africa, Asia, ocean islands and polar regions are sparsely represented The geographical bias inherent in any global dataset will propagate into all studies This bias can be reduced (but not eliminated) by treating regional subsets of the dataset as independent information, as has been done in the recent studies described above

The problem of geographical bias is now being addressed with the establishment of the Global Level of the Sea Surface (GLOSS) global tide gauge network coordinated by the Intergovernmental Oceanographic Commission (IOC) (Pugh, 1990) Most islands involved now have tide gauges and most continental GLOSS stations (other than polar sites) are now operational, but much work remains to improve standards and the reliability of observations

Finally, perhaps the most important source of error stems from the difficulties involved in removing vertical land movements from the dataset In addition to the effects noted above, most mid-latitude stations located on continental margins are especially susceptible to effects from sedimentation, groundwater and oil extraction, and tectonic influences and could be undergoing general submergence, which, unless accounted for, could introduce a positive bias into any global MSL secular trend (Pirazzoli et al , 1987) In order to identify a globally-coherent trend that can be linked to changes in global climate, such effects have to be removed The issue is how to do so

In the future, the inherent ambiguity between land and ocean level changes in a tide gauge record will be solved by the use of advanced geodetic methods, but such data are not available for present analysis (Carter et al , 1989) In lieu of new geodetic data, one approach adopted by recent analyses has been to model explicitly the expected geology-induced MSL changes at each tide gauge site by the use of ancillary Holocene data (e g , molluscs, corals, peats Gornitz et al , 1982, Gornitz and Lebedeff, 1987) or by the use of geodynamic models of the Earth (Peltier and Tushingham, 1989, 1990) The other approach is simply to assemble a sufficiently broad geographical spread of records such that (it is hoped) the net contribution of land movements reduces to zero (Barnett 1983 1984 1988)

These differences in approach probably account substantially for the different results noted in Table 9 1 But it cannot be said with confidence that vertical land movements (or, that is the failure to account adequately for them), along with reliance on a single dataset and problems of geographical bias, have not systematically biased all studies in the same direction

### 9.3.3 *Accelerations in Sea Level Rise*

Is there evidence of any "accelerations" (or departures from long-term linear trends) in the rate of sea level rise? From examinations of both composite regional and global curves and individual tide gauge records, there is no convincing evidence of an acceleration in global sea level rise during the twentieth century For longer periods, however, there is weak evidence for an acceleration over the last 2-3 centuries

Long-term analyses are hindered by the scarcity of tide-gauge records longer than 100-120 years Data are limited to a few stations in Europe and North America Woodworth (1990) inspected individual tide gauge records in Europe and found that although there is no general evidence for an increasing (or decreasing) rate of MSL change during the past century, a regionally-coherent acceleration of the order of 0 4mm/year per century is apparent over the last 2-3 centuries This finding is supported by Gornitz and Solow (1989) who find weak evidence for an increase in the trend around 1895 Similar conclusions were reached by Ekman (1988) from an examination of one of the longest tide-gauge records, at Stockholm Extension of such findings to the global scale, however should be carried out with caution

We now turn to the possible contributing factors to see if we can explain the past rise

## 9.4 Possible Contributing Factors To Past and Future Sea Level Rise

There are four major climate-related factors that could possibly explain a rise in global MSL on the 100-year time scale These are

1) thermal expansion of the oceans,
2) glaciers and small ice caps,
3) the Greenland ice sheet, and
4) the Antarctic ice sheet (including the special case of the West Antarctic ice sheet)

In this section, we examine the sensitivity of each factor to changes in climate (particularly temperature), and estimate its possible contribution to past sea level change In the subsequent section, attention is then turned to future sea level change

### 9.4.1 *Thermal Expansion of The Oceans*

At constant mass, the volume of the oceans, and thus sea level, will vary with changes in the density of sea-water Density is inversely related to temperature Thus as the oceans warm, density decreases and the oceans expand - a steric rise in sea level. Marked regional variations in sea water density and volume can also result from changes in salinity, but this effect is relatively minor at the global scale.

In order to estimate oceanic expansion (past or future) changes in the interior temperature, salinity and density of the oceans have to be considered, either empirically or by models. Unfortunately, observational data are scant, both in time and space (Barnett, 1985). A few recent analyses have been carried out on the limited time-series data. For instance, Roemmich (1985) examined the 1955-1981 Panulirus series of deep hydrographic stations off Bermuda and Thomson and Tabata (1987) examined the Station PAPA (northeast Pacific Ocean) steric height anomalies for a similar 27-year record. The latter study found that open ocean steric heights are increasing linearly at 0.93mm/year. However, in this and other studies, the large interannual variability creates too much "noise" to be confident of the estimate derived from such a short time-series. Moreover, the limited geographical coverage makes inference to the global scale problematic. In a few decades, current efforts such as the World Ocean Circulation Experiment (WOCE) will be begin to fill the data gaps and overcome these problems.

An alternative approach could be based on numerical models of the ocean's circulation (Barnett, 1985). Ideally, detailed three-dimensional models could describe the various oceanic mixing processes and could simulate heat transfer and expansion effects throughout the oceans. However, such models are in the early stages of development and applications to problems of global warming and thermal expansion are few in number. A drawback of this sort of model is that the computing time required precludes numerous runs for sensitivity analyses.

Instead, for the present assessment, a simple upwelling-diffusion energy-balance climate model is used. Typically this type of model represents the world's land and oceans by a few "boxes" and complicated processes of oceanic mixing are simplified in one or more parameters (for review see Hoffert and Flannery, 1985). Such a model was used to estimate the transient global warming (see Sections 6 and 8 for other results, and Section 8 for the justification for using this type of model). The inclusion of expansion coefficients in the model (varying with depth and possibly latitude) allows the sea level changes to be estimated as well. In order to maintain consistency throughout this assessment, both past and future (see below) thermal expansion effects are also estimated with this modelling technique, bearing in mind that full understanding of the dynamic processes and their effects on the depths and timing of ocean warming will eventually require more physically realistic models.

The model of Wigley and Raper (1989) was forced by past changes in radiative forcing due to increasing atmospheric concentrations of greenhouse gases (see Section 2). The internal model parameters that most affect the output are the diffusivity (K), the sinking water to global mean temperature change ratio ($\pi$) and the climate sensitivity ($\Delta T_{2x}$, the global-mean equilibrium temperature change for a $CO_2$ doubling) (see Section 6). In order to estimate past thermal expansion effects, the parameter values were constrained to maintain consistency with

***Table 9.3*** *Some physical characteristics of glacier ice on Earth. Sources: Flint (1971), Radok et al. (1982), Drewry (1983), Haeberli et al. (1988), Ohmura and Reeh (1990). Estimated accuracy: † =15%, †† = 30%, otherwise better than 10%.*

| | **Antarctica (grounded ice)** | **Greenland** | **Glaciers & small ice caps** |
|---|---|---|---|
| Area ($10^6$ km$^2$) | 11.97 | 1.68 | 0.55 |
| Volume ($10^6$ km$^3$ ice) | 29.33 | 2.95 | 0.11 †† |
| Mean thickness (m) | 2,488 | 1,575 | 200 †† |
| Mean elevation (m) | 2,000 | 2,080 | - |
| Equivalent sea level (m) | 65 | 7 | 0.35 †† |
| Accumulation ($10^{12}$ kg/yr) | 2200 †† | 535 † | - |
| Ablation ($10^{12}$ kg/yr) | < 10 †† | 280 †† | - |
| Calving ($10^{12}$ kg/yr) | 2200 †† | 255 †† | - |
| Mean equilibrium line altitude (m) | | 950 † | 0 - 6,300 |
| Mass turnover time (yr) | ~15,000 | ~5,000 | 50 - 1,000 |

observed global warming over the same time period (i.e , 0.3 - 0.6°C; see Section 7). For the period 1880-1985, the resultant range of sea level rise due to thermal expansion is about 2-6cm (also see Wigley and Raper, 1987; 1990).

### *9.4.2 Land Ice*

A distinction is made between glaciers and small ice caps, the Greenland ice sheet and the Antarctic ice sheet, since different climatic characteristics and different response times are involved. Table 9.3 lists some of their physical properties.

A large uncertainty exists regarding the volume of glaciers and small ice caps. Although the total area is relatively well-known (Haeberli et al., 1988), the mean thickness is not. Here a value of 200m is adopted, which really is a first-order estimate. Fortunately, on small time scales, (up to several decades), it is the surface area that largely determines the changes in runoff.

Although the positive and negative contributions to the mass budget of the Greenland and Antarctic ice sheets noted in Table 9.3 sum up to zero, it is actually unknown how close the ice sheets are to equilibrium (a more detailed discussion is given below). This introduces the problem of choosing an initial state for model integrations to estimate future sea level. In a previous assessment (Oerlemans, 1989), the year AD 1850 was taken as a starting point, and it was suggested to simply add the "unexplained part" of past sea level rise to the calculated future contributions from thermal expansion and land ice. The unexplained trend can also be associated with long-term changes of the ice sheets, but also to unknown tectonic effects. We return to this particular problem later.

From Table 9.3 a notable difference between the Greenland and Antarctic ice is evident. On Greenland there is significant ablation (melting *and* runoff, evaporation); on Antarctica ablation is a negligible component in the total mass budget. This is also reflected in the altitude of the equilibrium line (= zero annual mass gain). It is instructive to consider this in the light of a generalised mass-balance curve, where mass gain and loss are plotted as a function of *annual* surface air temperature (Figure 9.3). The resulting mass balance is in metres of water equivalent per year. Depending on the annual temperature range, ablation occurs for annual temperatures higher than -15 to -10°C. At the lower reaches, accumulation increases with temperature, reaches a maximum in the vicinity of the freezing point and then decreases.

The net specific balance thus shows two ranges with different behaviour. In range (a) mass balance increases with temperature, in range (b) it decreases with temperature. This makes the response of ice masses to climatic change complicated. Most glaciers and the Greenland ice sheet are mainly, but not entirely, in region (b). The Antarctic ice sheet with its much colder climate is situated in region (a). In case of a climatic warming, one expects an increasing surface mass balance for the Antarctic ice sheet (contributing to a sea level lowering) and a decreasing mass balance for the other ice bodies (contributing to sea level rise).

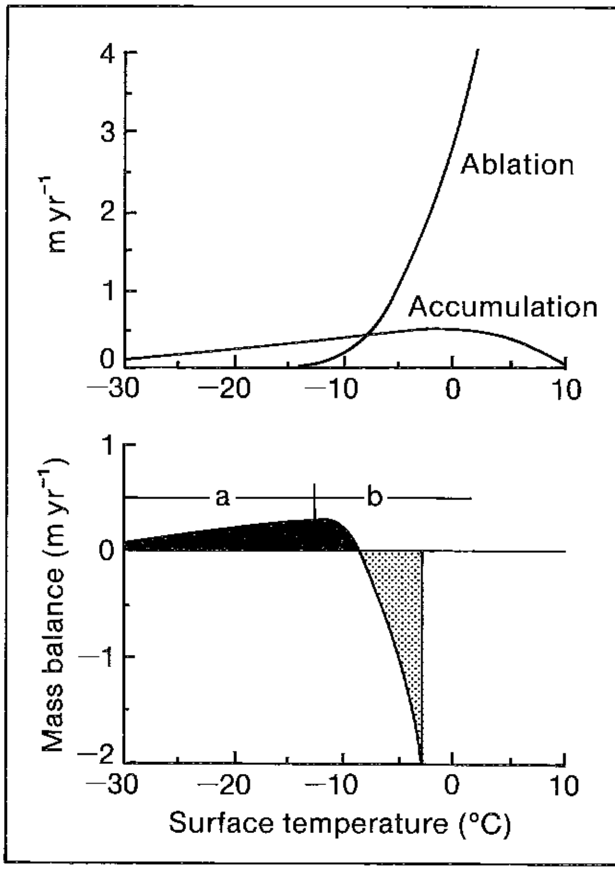


**Figure 9.3:** Dependence of ablation (evaporation and runoff) and accumulation on annual surface temperature (upper panel). The dependence of net annual balance (lower panel) on temperature changes sign, which complicates the response of glaciers to climate change. The picture is schematic and will change from place to place. In regions with excessive precipitation, the mean temperature at equilibrium is higher.

### *9.4.3 Glaciers and Small Ice Caps*

The majority of valley glaciers has been retreating over the last hundred years. Although long records of glacier length are only available for some glaciers in the European-North Atlantic region (Figure 9.4), geomorphological investigations have made it clear that the trend of glacier retreat has generally been world-wide since the Little Ice Age (Grove, 1988). Wastage was most pronounced in the middle of the 20th century. Around 1960, many glaciers started to advance. In the 1980s this advance slowed down

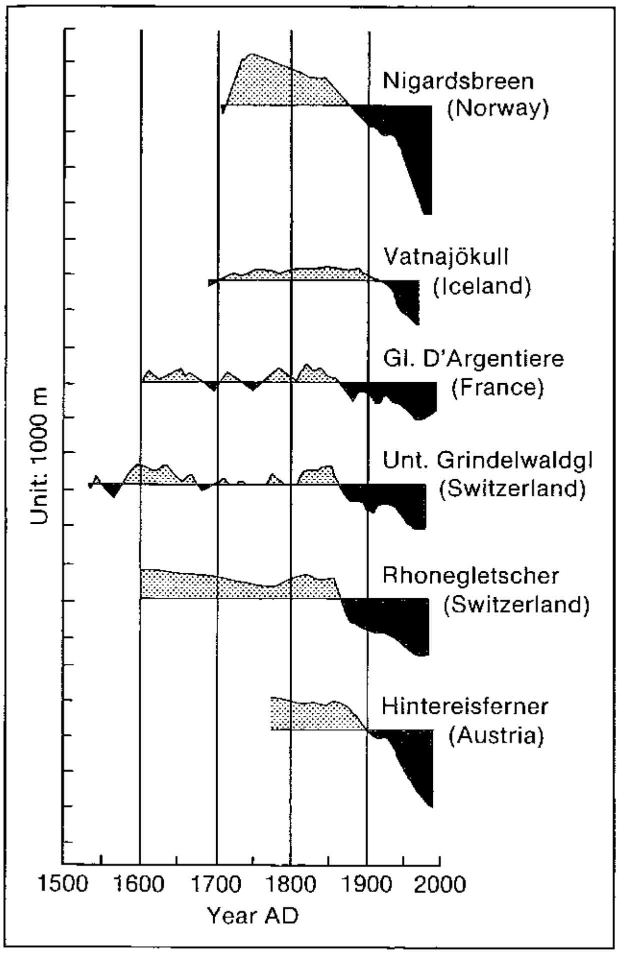


**Figure 9.4:** Variations of some selected glaciers as measured by their length. Data from Bjornsson (1979); Ostrem et al. (1977); Kasser (1967, 1973); Kasser and Haeberli (1979); Muller (1977); Vivian (1975); Haeberli (1985).

or stopped in several glacier basins (e.g., Haeberli et al., 1989a), but not everywhere. In Scandinavia, for instance, mass balance remained positive on the maritime glaciers and close to zero on the others.

The main published estimate of the contribution of retreating glaciers to past sea level rise is that of Meier (1984). In his analysis, Meier assumed that the magnitude of the long-term changes, for which data are sparse, are proportional to the difference between summer and winter balance, for which data are more abundant. This allowed extrapolation of measurements on a few glaciers to a world-wide scale. Meier estimated that during the period 1900-1961, glacier retreat contributed 2.8 cm, or 0.46 ± 0.26 mm $yr^{-1}$, to global sea level rise. By using data from three well-documented glaciers in temperate climate regions, Meier also extrapolated the record to encompass 1885-1974. This gives an average rate of sea level rise which is somewhat less than 0.46 mm $yr^{-1}$.

During the period 1900-1961, global mean temperature rose by approximately 0.35°C (see Section 7). This yields a sensitivity in terms of sea level rise of 1.3 mm $yr^{-1}$ per degree (with the ocean area equal to 361 million $km^2$).

This sensitivity value is broadly supported by mass balance studies. In the study noted above Meier found a net glacier *mass balance* of -0.38 ± 0.2m/yr for 25 well studied glaciers, converting to a sensitivity of -1 m $yr^{-1}$ per degree temperature rise. This can be compared to other, more direct estimates. For example, based on an analysis of 29 years of climatological and mass balance data from the Hintereisferner (a well-studied glacier in the Austrian Alps), Greuell (1989) finds a sensitivity of -0.41 m $yr^{-1}$ per degree warming. Kuhn (1990) suggest a global value of the order of -0.5 m $yr^{-1}$ per degree. Sensitivity tests with an energy balance model for a glacier surface, including albedo feedback, yields values ranging from -0.45 m $yr^{-1}$ per degree warming for drier climates to -0.7 m $yr^{-1}$ per degree warming for moist climates (Oerlemans, 1990). Altogether, these studies come up with smaller values than the -1 m $yr^{-1}$ per degree derived from Meier's estimate of change in glacier mass balance combined with a figure for the global temperature change. It is probably the use of this *global* temperature change from which the discrepancy arises. It is known that summer temperature is the important parameter, and it also seems unlikely that the mean change over the glacierized regions can be represented by the global mean temperature. The global sensitivity value inferred by these studies is 1.2± 0.6 mm $yr^{-1}$ per degree warming.

In our judgement glacier shrinkage will continue and accelerate in a warming climate.

### *9.4.4 The Greenland Ice Sheet.*

Estimates of the mass budget of the Greenland ice sheet have been hampered by a pronounced lack of data. Accumulation measurements have been done on a few traverses only (see Radok et al., 1982). Systematic ablation measurements in the marginal zone have been carried out in several places, but all located in the southwestern part of Greenland (Braithwaite and Oleson, 1989). The only profile from the ice margins to the region well above equilibrium line is the EGIG profile (Expedition Glaciologique Internationale au Groenland, West Greenland, at about 70°N latitude). Here mass balance and meteorological measurements have been carried out in the summer seasons of 1959 and 1967 (Ambach, 1963, 1979).

Table 9.4 lists estimates of the total mass budget of the Greenland ice sheet as compiled by Robin (1986). The differences appear quite large. The zeros in the column "balance" should not be interpreted as an indication for a balanced state - equilibrium has only been assumed. When going through the original papers it becomes clear that, on the basis of currently available data, there is considerable

***Table 9.4*** *Estimates of the mass budget of the Greenland ice sheet in $10^{12}$ kg/yr (updated from Robin, 1986)*

| Source | Accumulation | Ablation | Calving | Balance |
|---|---|---|---|---|
| Bader (1961) | +630 | -120 to -270 | -240 | +270 to +120 |
| Benson (1962) | +500 | 272 | -215 | +13 |
| Bauer (1968) | +500 | -330 | -280 | -110 |
| Weidick (1984) | +500 | 295 | -205 | 0 |
| Reeh (1985) | +487 | -169 | -318 | 0 |
| Ohmura & Reeh (1990) | +535 | | | |

***Table 9.5*** *Estimates of the sensitivity of the Greenland mass balance to climatic change T = temperature, P = precipitation, C = cloudiness Expressed in rate of change of global mean sea level (mm/yr)*

| Source | T (+1°C) | P (+5%) | C (+5%) | Remarks |
|---|---|---|---|---|
| Ambach & Kuhn (1989) | +0 31 | -0 13 | | Analysis of EGIG data |
| Bindschadler (1985) | +0 45 | | | EGIG data/retreating margin |
| Braithwaite and Olesen (1990) | +0 36 to +0 48 | | | Energy balance calculation |
| Oerlemans (1990) | +0 37 | 0 11 | -0 06 | Energy balance Model |

uncertainty regarding the current state of balance of the ice sheet An imbalance of up to 30% of the annual mass turnover cannot be excluded

A few studies have also been undertaken to detect changes in some selected area Along the EGIG line in central West Greenland, there is some indication of slight thickening in the interior part of the ice sheet A study along the Oregon State University line in South Greenland suggested a close balance between accumulation and ice discharge, at least in the interior part (Kostecka and Whillans, 1988)

On the basis of satellite altimetry Zwally (1989) found that the mass balance of the southern part of the ice sheet has been positive in the period 1978 1986 He reports that thickening of the ice sheet occurred in both the ablation and accumulation zone (order of magnitude 0 2 m/yr) Although there are doubts regarding the accuracy of the results (Douglas et al 1990) this work shows the enormous potential of radar altimetry to monitor changes on the large ice sheets

Most outlet glaciers for which observations exist (this is mainly in central and southern part of the west coast of Greenland) have retreated strongly over the last century (Weidick, 1984) As the retreat occurred in many regions, on a relatively short time scale (100 years), and in a period of significant warming in Greenland, increased ablation rates must be responsible for this However, the large ablation zones of the inland ice must have suffered from this too The implications for past sea level rise will be discussed shortly

A few estimates have been made of the sensitivity of Greenland mass balance to climatic change They are listed in Table 9 5 The method of Ambach and Kuhn (1989) is based on a new analysis of the EGIG data In their approach, the mass and energy budget at the equilibrium line is expanded with a linear perturbation technique, allowing the calculation of the change in the equilibrium-line altitude (dELA) associated with small changes in temperature, precipitation and radiation By extrapolating dELA to the entire ice sheet an estimate can then be made of the change in ablation and accumulation area and by assigning mass-balance values of the total ice mass budget Bindschadler's (1985) calculation is based on the same mass-balance measurements, but a (minor) correction is made for a retreating ice margin The value listed as Oerlemans et al (1990) results from a straightforward sensitivity test with an energy balance model applied to four regions of the ice sheet Braithwaite and Olesen (1990) have used an energy balance model to study their ablation measurements in southwest Greenland, and attempted to extrapolate the result to the entire ablation zone There is a reasonable agreement between all those studies, but this is partly due to dependence of the input

Above, only temperature has been considered as a climatic input parameter In fact, changes in the seasonal cycle, in precipitation and cloud patterns have occurred and will occur in the future The potential importance of such factors can be studied by sensitivity tests, and some results have been listed in Table 9 5 It has been suggested that even in the relatively warm climate of Greenland, snow accumulation may increase when temperature goes up (e g , Reeh and Gundestrup 1985) If annual precipitation would increase uniformly by 5% per degree warming, the precipitation effect can offset about 30% of the temperature effect Setting the annual precipitation proportional to the amount of precipitable water in a saturated atmospheric column [see Oerlemans and Van der Veen, 1984, p 140] would imply, for mean conditions over the Greenland ice sheet, a 4% increase in precipitation for a 1°C warming This leads to a best estimate of the sensitivity of 0 3 ± 0 2 mm yr $^{-1}$ per degree C The error bar is large because

i) There is considerable uncertainty on how precipitation patterns over Greenland will change in a warmer climate
ii) It is unknown whether iceberg calving from the outlet glaciers will increase due to increased basal water flow (Bindschadler, 1985) However the ice possibly involved in rapid retreat of calving fronts is almost afloat, so the contribution to sea level rise will be negligible Consequent thinning of grounded ice further upstream is not likely to affect sea level within the next 100 years
iii) It is unknown how factors like surface albedo and cloudiness will change

With a record of mean summer temperatures the sensitivity can be used to produce an estimate of Greenland s contribution to past sea level rise As shown in Figure 9 5, the 1866-1980 summer temperature departures (relative to the 20-year average for the reference period 1866-1885) shows an overall warming of about 0 5°C However the decadal changes are pronounced with a large warming of about 2°C occurring up to 1930 35 and a cooling trend thereafter By summing the product between the sensitivity value and the temperature departure for each year from 1880-1980, the 100-year contribution to sea level is estimated Assuming initial conditions in equilibrium and a sensitivity of 0 3 ± 0 2 mm yr $^{-1}$ per degree, the summation yields 23 ± 16 mm (or 0 23 ± 0 16 mm yr $^{-1}$) So the contribution from Greenland to past sea level rise appears to be somewhat less than that from glaciers and thermal expansion

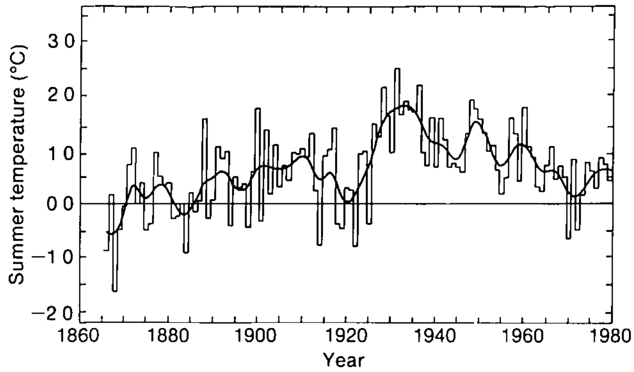


**Figure 9.5:** Summer (JJA) temperature (°C) as departures from reference period 1866 1885 averaged over Greenland The smoothed curve is a moving 10 year filter

### *9.4.5 The Antarctic Ice Sheet.*

The question of balance of the Antarctic ice sheet proves to be a very difficult one From a physical point of view regarding the very long time scale introduced by geodynamics and thermomechanical coupling in the ice sheet, it seems unlikely that the present ice sheet has adjusted completely to the last glacial-interglacial transition A detailed modelling study by Huybrechts (1990), in which a glacial cycle of the Antarctic ice sheet is simulated on a 40km grid suggests that the large scale imbalance will not be more than a few percent of the annual mass turnover (corresponding to a rate of sea level change of less than 0 1 mm yr $^{-1}$) This does not exclude the possibility however that climate fluctuations with a shorter time scale have pushed the ice sheet out of balance Also there is increasing evidence that marine ice sheets like the West Antarctic could exhibit pulsating mass discharge which is not climate related but may have important consequences for sea level

Budd and Smith (1985) made an assessment of the net balance by compiling a set of accumulation and ice velocity measurements (Table 9 6) The latter allow to make a rough estimate of the ice discharge from the main ice sheet across the grounding line viz 1879 x $10^{12}$ kg/yr They find a number of about 2088 x $10^{12}$ kg/yr for the accumulation and estimate the net balance to be positive by

***Table 9.6*** *Antarctic mass balance ($10^{12}$ kg/yr). † = without Antarctic Peninsula. Proper reference for SPRI (Scott Polar Research Institute) map and data: Drewry (1983).*

| | Flux at grounding line | Surface balance (*grounded* ice) | Net |
|---|---|---|---|
| Budd and Smith (1985) | ~1879 | 2088 | 0 to +418 |
| Digitization SPRI *map* Huybrechts (1990) | | 2168 | |
| Radok et al. (1986) | | 2158<br>1765 † | |
| Giovinetto and Bentley (1985) | | 1468 † | |
| Fortuin and Oerlemans (1990) [based on SPRI *data*] | | 1817 | |

209 x $10^{12}$ kg/yr. This would correspond to a rate of sea level change of about -0.6 mm $yr^{-1}$. Subsequent estimates of the total accumulation have produced lower values. Giovinetto and Bentley (1985) state that accumulation over the grounded part of the ice sheet is only 1468 x $10^{12}$kg/yr. With the mean value for discharge from above, this yields a net balance of -411 x $10^{12}$ kg/yr. Fortuin and Oerlemans (1990) find, on the basis of a data set independently compiled from the archives of the Scott Polar Research Institute (SPRI), a mass gain at the surface of 1817 x $10^{12}$ kg/yr. With the discharge number from Budd and Smith this then implies a net balance of 62 x $10^{12}$ kg/yr.

It must be stressed that the inference of ice mass discharge from a limited number of *surface* velocity measurements involves many uncertainties. The ratio of surface velocity to vertical mean velocity is such an uncertain factor. More seriously, outflow velocities vary dramatically from point to point, so lateral extrapolation and interpolation around the coast introduces very large errors. A comprehensive comparison of earlier estimates of the surface mass balance was given by Giovinetto and Bull (1987). Their discussion suggests that the total surface accumulation over grounded ice is not known to an accuracy better than 10%. When considering the net balance, this figure will be worse.

In conclusion, it is unknown whether the Antarctic ice sheet is currently in balance and whether it has been contributing to sea level rise over the last 100 years or not. A 20% imbalance of mass turnover cannot be detected in a definite way from present data.

Several methods exist to investigate how accumulation on the Antarctic ice sheet may change when temperature changes. Analysis of the gas content in the deep Antarctic ice cores gives an indication of how accumulation varied between glacial and interglacial conditions (Lorius et al., 1984; Jouzel et al., 1989). In fact, it gives support to the view that accumulation on the interior is roughly proportional to the saturation mixing ratio of water vapour in the air above the inversion, as first suggested by Robin (1977). Another method involves regression analysis on measured temperatures and accumulation rates (Muszynski, 1985; Fortuin and Oerlemans, 1990). However, it is not so clear that a relation between accumulation and temperature based on spatial variation can be applied to climatic change. It is also possible to use precipitation rates as predicted by general circulation models of the atmosphere. Although the quality of these models has increased gradually, simulation of the climate of the polar regions still shows serious shortcomings (Schlesinger, 1990) and the results concerning glacier mass balance must be considered with much caution. So far, a systematic comparison between observed accumulation on the ice sheets and output from such models has not yet been published.

Table 9.7 lists a number of estimates of the change in Antarctic mass balance for a uniform warming of 1 degree C. Muszynski's estimate is the highest: a decrease of 0.38 mm/yr in sea level. The multiple regression analysis reported in Fortuin and Oerlemans (1990) yields a substantially lower value. In this analysis, which was based on a much larger newly compiled data set, a distinction was made between ice shelves, escarpment region and interior. Accumulation is strongly related to both temperature and latitude parameters, which also have a high mutual

***Table 9.7** Estimates of the change in Antarctic mass balance for a 1°C warming $\Delta q_S$ represents saturation water vapour mixing ratio of air above the inversion*

| Source | Change in sea level (mm/yr) | Remarks |
|---|---|---|
| Muszynski (1985) | -0 38 | Regression on 208 data points |
| Fortuin and Oerlemans (1990) | -0 139 (interior)<br>-0 061 (escarpment)<br>-0 200 (total) | Regression on 486 data points (only grounded ice) |
| Proportional to water vapour mixing ratio | -0 34 | 20 km grid over grounded ice |

correlation Taking this correlation out leads to a significantly weaker temperature dependence of the accumulation, but it can be argued that this approach is preferable when considering climate sensitivity The value listed under "proportional to water vapour mixing ratio" was calculated by integrating over a 20km grid covering the entire ice sheet with temperatures extrapolated from the data set used in the multiple regression mentioned above The values thus obtained are rather close to the one suggested by Muszynski s work

Support for the idea that higher temperatures will lead to significantly larger accumulation also comes from observations on the Antarctic Peninsula Over the past 30 years temperature has gone up here by almost 2°C, whereas accumulation increased by as much as 25% in parallel with this (Peel and Mulvaney, 1988) Although this cannot be taken as proof of a causal relationship it is in line with the sensitivity estimates listed in Table 9 7 which span a factor of two

In summary, all quoted studies show an increase in accumulation with warming and thus a decrease in sea level An ablation zone does not effectively exist in Antarctica, and a large warming would be required in order for ablation to influence mass balance

***9.4.6 Possible Instability of The West Antarctic Ice Sheet.*** Most of the early attention to the issue of sea level rise and greenhouse warming was related to the stability of the West Antarctic ice sheet Parts of this ice sheet are grounded far below sea level and may be very sensitive to small changes in sea level or melting rates at the base of adjacent ice shelves (e g Mercer 1978 Thomas et al 1979, Lingle 1985 Van der Veen 1986) In case of a climatic warming such melting rates could increase and lead to disappearance of ice rises (places where the floating ice shelf runs aground) Reduced back stress on the main ice sheet and larger ice velocities may result, with subsequent thinning of the grounded ice and grounding-line retreat

It is hard to make quantitative statements about this mechanism Several attempts have been made to model this ice sheet shelf system and to study its sensitivity (Thomas et al , 1979 Lingle, 1985, Van der Veen 1986, 1987 Budd et al , 1987) Van der Veen (1986), in a rather extensive study, concludes that the earlier estimates of the sensitivity of West Antarctica were too large Budd et al (1987) also give an extensive discussion on the response of the West Antarctic ice sheet to a climatic warming Their considerations are based on a large number of numerical experiments with flow band models According to these experiments very large ice-shelf thinning rates (10 to 100 times present values) would be required to cause rapid disintegration of the West Antarctic ice sheet For a probably more realistic situation of a 50% increase in ice shelf thinning rate for a one-degree warming (order of magnitude) the associated sea level rise would be about 0 1mm/yr for the coming decades

Much of the drainage of the West Antarctic ice sheet goes through a number of fast flowing ice streams the dynamics of which were not properly included in the modelling studies mentioned above In recent years it has become clear from new observational studies (e g Bentley, 1987 Alley et al 1987 MacAyeal 1989) that those ice streams show much variability on a century and may be even decadal time scale Although much of this variability is probably not related directly to climate change it demonstrates the potential of this part of the ice sheet to react quickly to any change in boundary conditions A comprehensive model of the ice streams and their interaction with the main ice body does not yet exist unfortunately Still as argued by D R MacAyeal (abstract to the 1989-American Geophysical Union meeting on sea

*Table 9.8 Estimated contributions to sea-level rise over the last 100 years (in cm)*

| | LOW | BEST ESTIMATE | HIGH |
|---|---|---|---|
| Thermal expansion | 2 | 4 | 6 |
| Glaciers/small ice caps | 1 5 | 4 | 7 |
| Greenland Ice Sheet | 1 | 2 5 | 4 |
| Antarctic Ice Sheet | -5 | 0 | 5 |
| TOTAL | -0 5 | 10 5 | 22 |
| OBSERVED | 10 | 15 | 20 |

level change, unpublished), an extreme limit of the response of the West Antarctic ice sheet to greenhouse warming can be estimated In his view the accelerated discharge of ice only occurs in the regions where sufficient sub-glacial sediments (the lubricant for the ice streams) is present For a typical greenhouse warming scenario, the bulk of the increased mass outflow would occur between 100 and 200 years from now, and the actual projected West Antarctic contribution to sea level rise would be -10 cm after 100 yrs (increase in surface accumulation still dominating), +40 cm after 200 yrs, and +30 cm after 300 yrs (ice stream discharge stopped)

In summary, there is no firm evidence to suggest that the Antarctic ice sheet in general or the West Antarctic ice sheet in particular, have contributed either positively or negatively to past sea level rise On the whole, the sensitivity of Antarctica to climatic change is such that a future warming should lead to increased accumulation and thus a negative contribution to sea level change

### *9.4.7 Other Possible Contributions*

Sea level could also have been affected by net increases or decreases in surface and groundwater storage In particular, groundwater depletion (through pumping) and drainage of swamps, soils and wetlands would contribute to a MSL rise On the other hand, increases in surface storage capacity - especially large dams but also the combined effects of many small reservoirs and farm ponds - would detract from sea level

Decreases in groundwater levels are commonly reported from all over the world from many different environments This suggests that total groundwater storage volumes have been diminishing, particularly during the last 50 years Data are meagre, however One rough estimate (Meier, 1983, also see Robin, 1986) is that, globally, net depletion has amounted to about 2000km$^3$ (equivalent to 0 55cm in sea level) during this century Land drainage, particularly in Northwest Europe and North America over the last 100 years, has reduced soil and shallow groundwater storage over wide areas, but the actual amounts of water are difficult to estimate

Substantial increases in surface storage have occurred since the 1930s Newman and Fairbridge (1986) estimated that this has amounted to about 18750km$^3$ (-5 2cm in sea level, using 362 x 10$^6$km$^2$ for ocean area) over the period 1932-1982 Golubev (1983, Also see Robin, 1986), however, makes a much lower estimate, 5500km$^3$ (-1 5cm in sea level)

Overall, the estimates appear too imprecise and the data insufficient, especially for groundwater changes, to be able to conclude much about the possible net effects on past sea level rise

### *9.4.8 Synthesis*

The estimated contributions to past sea level rise can now be summarised (Table 9 8) Assuming the contribution from Antarctica has been zero, the combined contributions from thermal expansion, mountain glaciers and the Greenland ice sheet over the last 100 years total 10 5cm This is within the range of observed sea level rise (10 - 20cm), albeit at the lower end The range of uncertainty is large -0 5cm to 22cm

*Table 9.9* Estimates of future global sea level rise (cm) (Modified from Raper et al., 1990)

| | CONTRIBUTING FACTORS | | | | TOTAL RISE [a] | | |
|---|---|---|---|---|---|---|---|
| | Thermal Expansion | Alpine | Greenland | Antarctica | Best Estimate | Range [f] | To (Year) |
| Gornitz (1982) | 20 | 20 (Combined) | | | 40 | | 2050 |
| Revelle (1983) | 30 | 12 | 13 | | 71 [b] | | 2080 |
| Hoffman et al. (1983) | 28 to 115 | 28 to 230 (Combined) | | | | 56 to 345<br>26 to 39 | 2100<br>2025 |
| PRB (1985) | c | 10 to 30 | 10 to 30 | -10 to 100 | | 10 to 160 | 2100 |
| Hoffman et al. (1986) | 28 to 83 | 12 to 37 | 6 to 27 | 12 to 220 | | 58 to 367<br>10 to 21 | 2100<br>2025 |
| Robin (1986) [d] | 30 to 60 [d] | 20±12 [d] | to +10 [d] | to -10[d] | 80 [i] | 25 - 165 [i] | 2080 |
| Thomas (1986) | 28 to 83 | 14 to 35 | 9 to 45 | 13 to 80 | 100 | 60 to 230 | 2100 |
| Villach (1987) (Jaeger, 1988) [d] | | | | | 30 | -2 to 51 | 2025 |
| Raper et al. (1990) | 4 to 18 | 2 to 19 | 1 to 4 | -2 to 3 | 21 [g] | 5 to 44 [g] | 2030 |
| Oerlemans (1989) | | | | | 20 | 0 to 40 | 2025 |
| Van der Veen (1988) [h] | 8 to 16 | 10 to 25 | 0 to 10 | -5 to 0 | | 28 to 66 | 2085 |

a - from the 1980s
b - total includes additional 17cm for trend extrapolation
c - not considered
d - for global warming of 3.5°C
f - extreme ranges, not always directly comparable
g - internally consistent synthesis of components
h - for a global warming of 2-4°C
i - estimated from global sea level and temperature change from 1880-1980 and global warming of 3.5±2.0°C for 1980-2080

## 9.5 How Might Sea Level Change in the Future?

Various estimates of future sea level rise are noted in Table 9.9. Such estimates are very difficult to compare because different time periods are chosen, and because assumptions regarding future greenhouse gas concentrations, changes in climate, response times, etc., are either different or not clearly stated. In general, most of the studies in Table 9.9 foresee a sea level rise of somewhere between 10cm and 30cm over the next four decades. This represents a rate of rise that is significantly faster than that experienced, on average, over the last 100 years.

Projections for the present assessment are made using the standard IPCC greenhouse gas forcing scenarios. These consist of a "Business-as-Usual" scenario, and three lower scenarios (B-D) in which greenhouse gas emissions are substantially reduced. Three projections are made for each scenario (12 projections in total) reflecting the high, low and best-estimate assumptions for each of the contributing factors, as described below

### *9.5.1 Methods and Assumptions*

Estimates of the thermal expansion effects are obtained using the upwelling-diffusion model of Wigley and Raper (1987) described in 9 4 1 and in Section 6 For each scenario, the model is run using a climate sensitivity ($\Delta T_{2x}$) of 1 5°C, 2 5°C and 4 5°C for the low, best-estimate and high projections, respectively, with the diffusivity set to 0 63cm$^2$sec$^{-1}$ and $\pi$ set to 1 (see Section 6 for the justification of the choice of diffusivity and $\pi$ values)

Concerning glaciers and small ice caps, significant warming may decrease the ice-covered area within a hundred years Thus, in order to make realistic estimates of the glacier contribution, the changes in glacier area have to be taken into account This is accomplished using a simple, global glacier melt model (Raper et al , 1990) The model contains three parameters that have to be prescribed initial ice volume, a global-mean glacier response time and a representative glacier temperature sensitivity parameter The parameter values were chosen to match estimated rates of glacier volume loss over the last 100 years The model was run from 1861 to 2100 (implying that, at present, glaciers are in disequilibrium)

With respect to the Greenland and Antarctic ice sheets (including the West Antarctic ice sheet and the Antarctic Peninsula), the dynamic response can effectively be ignored for the time-scales considered here The static changes in the surface mass balance can thus be represented by the sensitivity values discussed above, that is

$\Delta h$ = 0 3 ± 0 2mm/yr per degree for the Greenland ice sheet

$\Delta h$ = -0 3 ± 0 3mm/yr per degree for the Antarctic ice sheet

Based on the latest results from transient runs of fully-coupled ocean-atmosphere GCM's (Stouffer et al , 1989), it was assumed that temperature changes were equivalent to the global mean, except in Greenland where temperature changes were enhanced by a factor of 1 5

### *9.5.2 Discussion*

The resultant projections of global sea level rise to the year 2100 are shown in Figures 9 6 and 9 7 Under the Business-as-Usual scenario, the best estimate is that, for the year 2030, global sea level would be 18cm higher than today Given the stated range of uncertainty in the contributing factors, the rise could be as little as 8cm or as high as 29cm By the year 2070, the projected range is 21-71cm with a best-estimate of 44cm, although it should be cautioned that projections this far into the future are fraught with many uncertainties, many of which are external to thermal expansion and land ice melting

The major contributing factors to the sea level rise are thermal expansion of the oceans and glaciers and small ice caps The minor contributions to sea level from the Greenland and Antarctic ice sheets are positive and negative, respectively (Table 9 10)

For scenarios B, C and D (Figure 9 7), the sets of projections are similar This is because with low forcing scenarios, the temperature and sea level effects are more sensitive to $\Delta T_{2x}$ and the history of forcing change up to 1990 than to forcing change post-1990 The best-estimates for the year 2070 fall in the range 27-33cm, about one-third less than the Business-as-Usual case

The fact that sea level continues to rise throughout the 21st century - even under scenarios of strict emission reductions demonstrates the strong effect of past changes in greenhouse gas concentrations on future climate and sea level This is because of the lag effects introduced by the thermal inertia of the oceans and the continuing response of land ice to climate changes In effect, this creates a very substantial sea level rise "commitment" This is illustrated

***Table 9.10*** *Factors contributing to sea level rise (cm), 1985 - 2030 "Business-as-Usual" Scenario - Best Estimate for 2030*

| | Thermal Expansion | Mountain Glaciers | Greenland | Antarctica | TOTAL |
|---|---|---|---|---|---|
| HIGH | 14 9 | 10 3 | 3 7 | 0 0 | 28 9 |
| BEST ESTIMATE | 10 1 | 7 0 | 1 8 | -0 6 | 18 3 |
| LOW | 6 8 | 2 3 | 0 5 | 0 8 | 8 7 |

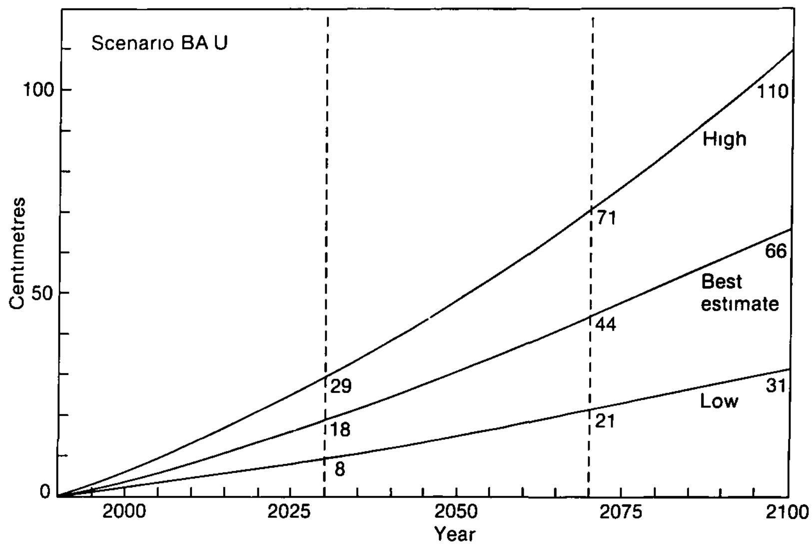


**Figure 9.6:** Global sea-level rise, 1990-2100, for Policy Scenario Business-as-Usual

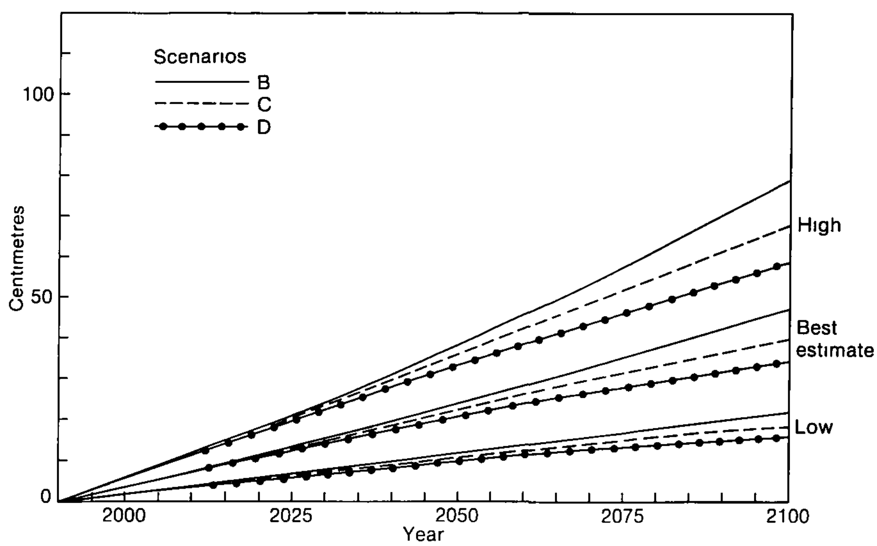


**Figure 9.7:** Global sea-level rise, 1990-2100, for Policy Scenarios B, C, D

in Figure 9 8 Here, the IPCC "Business-as-Usual" Scenario of greenhouse forcing is imposed to the year 2030 with no further changes in forcing thereafter Sea level, however, continues to rise at almost the same rate for the remainder of the century

This section has been concerned primarily with *global* mean sea level rise It should be borne in mind that sea level will not rise uniformly around the world First at any given coastal location sea level will be influenced by local and regional vertical land movements In some circumstances, these are large and will mask climate related changes in ocean volume Second, dynamic processes in the ocean and atmospheric circulation will also cause sea level to change regionally For example, a sensitivity study with a dynamic ocean model showed regional differences of up to a factor of two relative to the global-mean value (Mikolajewicz et al , 1990) Finally, changes in the frequency of extreme sea level events may be most important in their impact on coastal zones, but are currently difficult to quantify because of the uncertainties in regional predictions of climatic change

In general for the coming decades the present best estimate projection of sea level rise for the Business as-

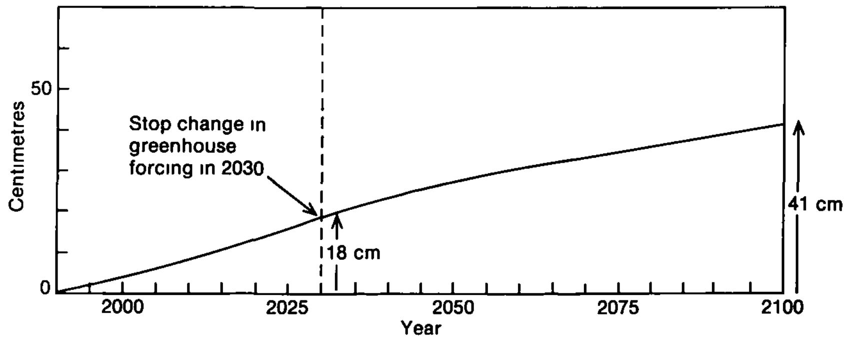


**Figure 9.8:** Commitment to sea level rise in the year 2030 The curve shows the sea level rise due to Business-as-Usual emissions to 2030, with the additional rise that would occur in the remainder of the century even if climate forcing was stabilised in 2030

Usual case does not represent a major departure from those found in the most recent literature (Table 9 9)

## 9.6 Summary and Conclusions

This chapter has addressed three questions

- Has global-mean sea level been rising over the last 100 years?
- What are the causal factors that could explain a past rise in sea level? and,
- What increases in sea level can be expected in the future?

The array of data and methodological problems inherent in estimating the rate of past sea level change is large The selection of data and its manipulation can make a difference of more than a factor of two in the global trend estimate While recent analyses of MSL trends involve more refined means of data correction and analysis, they generally support, not alter, the broad conclusions of previous assessments It is our judgement that

- Global sea level has been rising
- The average rate of rise over the last 100 years has been 1 0 - 2 0mm/yr
- There is no firm evidence of an acceleration in global MSL rise over this century (although there is some evidence that sea level rose faster in this century compared to the previous two centuries)

It appears that the past rise in sea level is due largely to thermal expansion of the oceans and increased melting of glaciers and the margins of the Greenland ice sheet There is no firm basis for supposing that the Antarctic ice sheet has contributed either positively or negatively to past sea level change In general, these findings support the conclusion, based on analyses of tide gauge records that there has been a globally-coherent, secular rise in sea level, and that the causes are most likely related to climatic change

*Future* changes in sea level were estimated for each of the IPCC forcing scenarios For each scenario, three projections - best estimate, high and low - were made corresponding to the estimated range of uncertainty in each of the potential contributing factors, and in the climate sensitivity and resulting global warming predictions

*It is found that*

- For the 'Business-as-Usual" Scenario at year 2030, global-mean sea level is 8-29cm higher than today, with a best-estimate of 18cm At the year 2070, the rise is 21-71cm, with a best-estimate of 44cm
- Most of the contribution is estimated to derive from thermal expansion of the oceans and the increased melting of mountain glaciers
- The Antarctic ice sheet contributes negatively to sea level due to increased accumulation associated with warming Increased outflow of ice from the West Antarctic ice sheet is likely to be limited, but the uncertainty is large
- The Greenland ice sheet contributes positively to sea level rise, but part of the enhanced melting and runoff may be offset by increased snowfall in the higher parts, so the uncertainties are very large
- For the lower forcing scenarios (B,C and D), the sea level rise projections are similar, at least until the mid-21st century On average these projections are approximately one-third lower than those of the "Business-as-Usual" Scenario

Even with substantial decreases in the emissions of the major greenhouse gases future increases in sea level are unavoidable - a sea level rise commitment' - due to lags in the climate system

In general, this review concludes that a rise of more than 1 metre over the next century is unlikely Even so, the rate of rise implied by the Business-as-Usual best-estimate is 3-6 times faster than that experienced over the last 100 years The prospect of such an increase in the rate of sea level rise should be of major concern to many low-lying coasts subject to permanent and temporary inundation, salt intrusion, cliff and beach erosion, and other deleterious effects

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