A PROJECTION OF FUTURE SEA LEVEL

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Abstract. Evidence is reviewed that suggests faster sea-level rise when climate gets warmer. Four processes appear as dominating on a time scale of decades to centuries: melting of mountain glaciers and small ice caps, changes in the mass balance of the large polar ice sheets (Greenland, Antarctica), possible ice-flow instabilities (in particular on the West Antarctic Ice Sheet), and thermal expansion of ocean water.

For a given temperature scenario, an attempt is made to estimate the different contributions. The calculation yields a figure of 9.5 cm of sea-level rise since 1850 AD, which is within the uncertainty range of estimates of the 'observed' rise.

A further 33 cm rise is found as most likely for the year 2050, but the uncertainty is very large ($\sigma = 32$ cm). The contribution from melting of land ice is of the same order of magnitude as thermal expansion. The mass-balance effects of the major ice sheets tend to cancel to some extent (increasing accumulation on Antarctica, increasing ablation on Greenland). For the year 2100 a value of 66 cm above the present-day stand is found ($\sigma = 57$ cm). The estimates of the standard deviation include uncertainty in the temperature scenario, as presented elsewhere in this volume.

1. Introduction

Changes in global sea level are a potentially very important aspect of the greenhouse problem. Since many heavily populated areas in the world are close to sea level, even changes less than 1 m can have dramatic consequences. In particular since the appearance of Mercer's (1978) paper on possible instability of the West Antarctic Ice Sheet, a great deal of public attention has been focussed on sea-level rise. That the polar ice sheets will melt when the greenhouse warming comes, seems to be obvious to anyone.

However, as soon as more precise questions are asked, we (the few scientists studying the issue) are in trouble. We are able to identify a large number of mechanisms contributing to changes in sea level when climate changes, but a reliable figure of the total effect is hard to get. Our knowledge of the major ice sheets is particularly poor, which is understandable. There have hardly been any other than purely scientific reasons to do geophysical investigations in those remote and poorly accessible regions. Still, the question is asked frequently: *How fast will sea level rise in the near future?*

Climatic Change **15**: 151–174, 1989.
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Before dealing with this, a few other questions can be posed: Why did sea level rise over the last century? Is the present warming trend associated with increasing concentration of trace gases in the atmosphere or just a recovery from the little ice age? What would happen to the major ice sheets when climate would remain perfectly constant? Or to the deep ocean? One would like to find answers to these questions before embarking on a projection of *future* sea level. Unfortunately, we will not have the time and are thus forced to make the best of it. This could (and will) imply that the uncertainty in the projection will be of the same order of magnitude as the 'signal' itself.

Even the estimates of recent sea-level rise differ considerably (Barnett, 1983, 1984; Gornitz *et al.*, 1982; 1987). Much depends on how local effects are taken into account. Most workers put the rate of sea-level change over the last century between +9 and +15 cm.

Although the choice of a realistic temperature scenario is a crucial step in predicting changes in sea level, this point will be postponed to the end of this section. We will first identify and discuss the processes that are able to give a major contribution to world-wide sea level change.

It is obvious that changing circulation patterns in ocean and atmosphere will cause changes in sea level. First of all, the topography of the sea surface is in a dynamic balance with the currents: an intensified North Atlantic gyre, for instance, would lead to a larger difference in sea level between the central Atlantic and the coasts. Also, changes in mean atmospheric pressure may make the sea rise or sink. In shallow coastal waters, a change in mean wind stress will lead to a change in the 'mean' component of the wind set-up. Still, these processes are of a local character and nearly balance when averaged over the entire globe. The order-of-magnitude of such local changes in sea level is not impressive: maybe 10 cm at most for changes in atmospheric circulation that could occur as a consequence of the enhanced greenhouse forcing.

In fact, since we are interested in changes on a time scale of decades to a few centuries, it appears that only a few processes are capable of producing substantial changes in sea level when climate really gets warmer. These are thermal expansion of ocean water and changes in land ice volume. It is useful to split the latter in contributions from mountain glaciers, from the large polar ice sheets (Greenland, Antarctica), and from possible ice-flow instabilities [most importantly, but not exclusively, the West Antarctic Ice Sheet (WAIS)], see Figure 1. In general, the change in relative sea level is determined by the change in ocean volume and the response of the solid earth. Any change in loading will lead to an elastic as well as a viscous reponse, which will vary from place to place. It is now well accepted that a proper interpretation of proxy sea-level data is not possible without the use of sophisticated earth models (e.g. Clark, 1980; Peltier, 1988). However, for the present purpose a treatment of the geodynamical response is not necessary.

Some general characteristics of land ice are given in Table I. The Antarctic Ice Sheet is by far the largest ice mass: its volume is about ten times that of the Green-