SEA LEVEL AND CLIMATE VARIATIONS

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ABSTRACT

Sea level is an essential component of the climate system, on which many human activities in the coastal zone depend. Climate variations leading to changes in relative sea level are discussed, with some emphasis on the possible effects of a carbon dioxide warming. Variations in land ice volume are probably most important. Suggestions are given of how future satellite data may help in monitoring and understanding of global variations in sea level.

Keywords: Sea level, Carbon dioxide problem, Climatic change, Climate modelling.

1. INTRODUCTION

It is natural to consider sea level as a climatic parameter. Variations in sea level, even of the order of 10 or 20 centimeters, can have a large impact on human activities. Many of the world's major cities have an elevation close to sea level, which is a good reason to pay attention to sea-level variations.

Interest in sea level increased enormously when climatologists started to mention the possibility of a substantial warming (a few degrees K) within the next century, due to the antrophogenic carbon dioxide emission. A paper by Mercer (Ref. 1) draw particular attention. He suggested that a climatic warming could trigger a disintegration of the main part of the West Antarctic Ice Sheet, which would cause a rise in global sea level of about 5 m in a period of no longer than a few centuries.

The primary argument for the possibility of such a collapse came from paleoclimatic information on the 125 000 yr BP interglacial. Some (scarce) data on sea-level stands indicate for that time a 5 m higher stand (compared to the present day). See for instance Ref. 2. Together with proxy data concerning prevailing climatic conditions, pointing to the presence of a climate with temperatures a few degrees above present-day values, this suggests that the West Antarctic Ice Sheet did not exist at that time. Although many questions have been raised about the arguments, Mercer's paper has certainly brought sea level the attention that it deserves.

It is a fact that over the last hundred years relative sea level went up in most places over the world. For a critical assessment, see for instance Ref. 3. Although debate concerning the average rate of sea-level rise is going on, most workers agree on a figure between 10 and 20 cm per century. Various reasons have been put forward explaining this observation. Thermal expansion of sea water and melting of small glaciers and ice caps, or a combination of both, are the most popular explanations. We return to this later.

2. FACTORS GOVERNING SEA LEVEL

First of all it is useful to make a distinction between eustatic and relative sea level. Although eustatic sea level is not a sharply defined term, one may think of it to be closely related to the total ocean volume. Changes in eustatic sea level are the result of melting or growth of ice sheets and glaciers, variations in groundwater storage and in the body of water contained in lakes and inland seas. Table 1 gives an impression of how the present mass of water is distributed over the various reservoirs.

	present	ice age	res. time
oceans	1 370 000	1 330 000	3000
land ice	24 000	64 000	15 000
groundwater	64 000	?	10 000
lakes	230	?	10
soil	80	?	0.5
atmosphere	13	11	0.02

Table 1. *Some data on the water budget of the earth, from Ref. 4 with some additions. Volumes are in 10^{12} m^3, residence times in years. Residence time for land ice refers to ice sheets, glaciers have a much shorter turnover time (centuries).*

One generally agrees on the fact that in late pleistocene and holocene times most of the changes in eustatic sea level were due to melting and built-up of large ice sheets, notably the Laurentide and Fennoskandian ice sheets. Very little is known about the reservoir referred to as ground-

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water. Because variations in the storage of ground water are intimately related to changes in the surface water balance, this factor may be important. Note that the reservoirs of land ice and groundwater contain a roughly equal amount of mass, and have comparable time scales.

Eustatic sea level may also change due to variations in the mean density of ocean water. In particular thermal expansion cannot be disregarded. A 1 K increase in the mean temperature of the oceanic mixed layer will cause a rise of eustatic sea level of the order of a few centimeters.

Relative sea level is closely related to crustal movements. Any change in loading of the crust (sediments, water, ice) will result in an instantaneous elastic and a slow viscous response of the earth, causing changes in relative sea level. To this come the crustal movements of tectonic origin. In the last decade a number of numerical models has been developed for the calculation of sea-level histories (e.g. Refs. 5-7). These models have been applied to the glacial-interglacial transition event. With the deglaciation chronology as input, predicted sea-level curves result. Although the models are yet far from perfect, they have shown that the response of sea level to changes in loading is far from simple, and they have shed another light on proxy sea-level records, in particular those of the equatorial zone. For more detail on this matter the reader is referred to Refs. 8-9.

The atmospheric and oceanic circulation also effect relative sea level. Variations in atmospheric pressure have a direct effect on sea level, while the action of the wind gives a significant contribution in shallow seas. Ocean currents are to a large extent in geostrophic balance, and the slope of the sea surface across a current is therefore governed by their strength. So changes in the pattern of ocean currents will effect local sea-level stands. A typical order of magnitude may be 10 cm.

In practice, relative sea level is the important element because this is what influences human activities. On time scales of more than a few centuries, changes in ocean volume have an effect on relative sea level comparable to that of isostatic and tectonic crustal movement. On shorter time scales, the latter is probably not less important, but certainly of a more constant nature.

3. CARBON DIOXIDE AND SEA LEVEL

Estimating future changes in sea level associated with antropogenic carbon dioxide input into the atmosphere is a difficult matter. A number of reports have been published in which figures were presented. It is obvious that such figures are tentative, because in any analysis one uncertainty is piled upon the other.

There is only one thing we are sure about: the carbon dioxide concentration in the atmosphere increases rapidly. The response of the climate system to this input is subject to continuous debate (e.g. Refs. 10-12). Nevertheless, the general opinion is that climate will become warmer by a few degrees K, with the largest effects in the polar regions. Scenarios have been presented in which climatic zones shift over the globe, thereby drastically changing the water balance at the surface, for instance. In the author's view, the present state of understanding the climate system is too poor to consider such detail seriously.

Determination of how sea level will react is the next step, and the introduction of additional uncertainty cannot be avoided. First consider Figure 1.

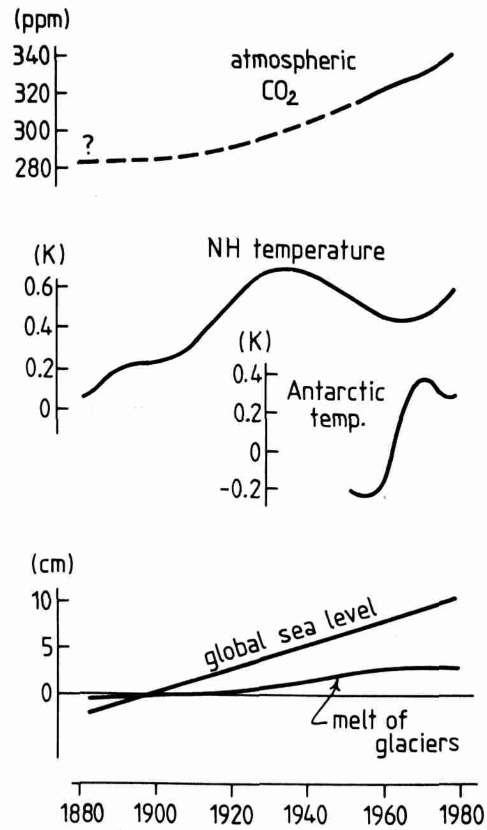

Figure 1. Some 'facts' relevant to the carbon dioxide problem.

The upper curve shows the atmospheric carbon dioxide concentration, see Ref. 10 for a discussion on measurements. There is no general agreement on the pre-industrial value, but 280 ppm for 1880 seems to be reasonable. Northern Hemisphere and Antarctic surface air temperatures are from Ref. 13. The data have been smoothed. An upward tendency is certainly present, but the 1940 maximum cannot be explained in terms of carbon dioxide effects. Recent attempts to model the Northern Hemisphere temperature curve by taking into account volcanism, solar activity and carbon dioxide seem to be rather succesful (e.g. Ref. 14). The record from the Antarctic zone is definitely too short to draw conclusions.

The sea-level trend in the lower part of the figure is the one suggested by Barnett (Ref. 3). Meier recently made an estimate of mass loss from glaciers (Ref. 15). Although his method relies on assumptions concerning spatial homogeneity that are sometimes difficult to verify, it probably gives a good indication. It turns out that about one third of the eustatic sea-level rise can be explained by melting of glaciers. Meier, and others, suggest that the remaining part can to a large extent be explained by thermal expansion of sea water.

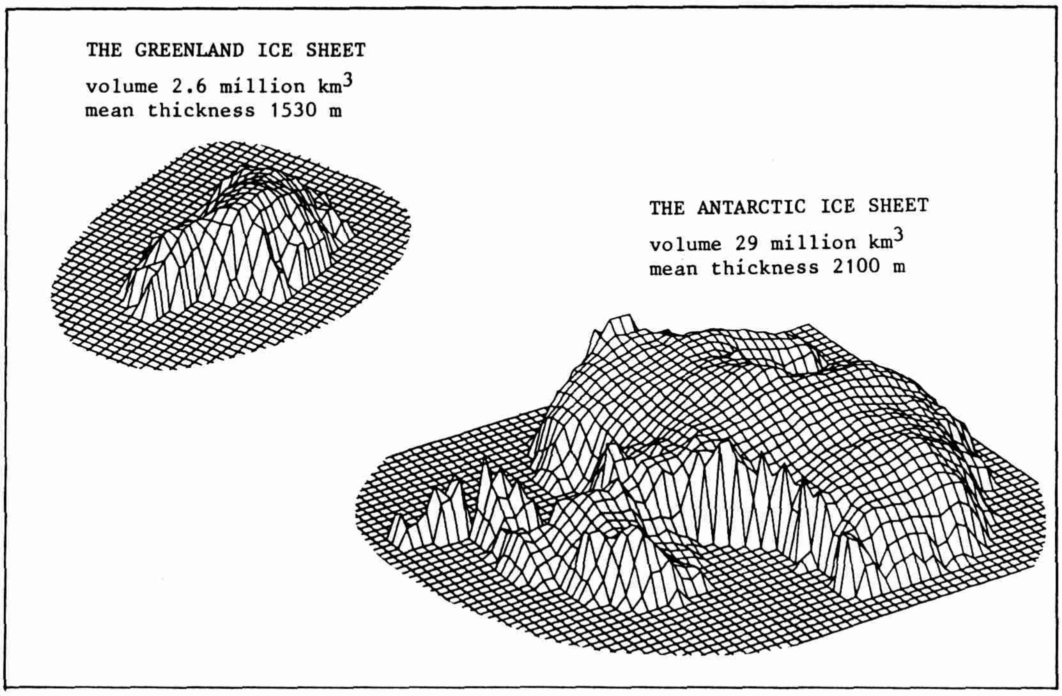

Figure 2. Isometric plots of the Greenland and Antarctic ice sheets. The grid parameter is 100 km.

Although the carbon dioxide 'signal' has not yet been found in temperature observations with definite statistical significance, the trends displayed in Figure 1 call for a continuous study of sea level. As noted in Ref. 3, monitoring sea level is not an easy matter. The causes of recent sea level variations are not at all clear, and further model studies may help here.

Large variations in sea level, of the order of 1 m within a century, say, are only possible when substantial changes in the shape of the ice sheets of Greenland and Antarctica occur (Figure 2). There are basically three different ways in which these ice sheets react to a climatic warming:

(i) a change in the surface mass balance;
(ii) larger ice-mass discharge because the ice temperature increases;
(iii) grounding-line instability due to thinning of ice shelves.

Mechanism (i) has an immediate effect on eustatic sea level. One can be rather sure that the mass balance of the Greenland Ice Sheet will decrease when temperature goes up. Ambach estimates a 3% decrease in Greenland ice volume after 250 yr, in case of a 3 K warming (Ref. 16). For the Antarctic Ice Sheet the situation is different. Climatic conditions are much colder, and it can be expected that higher air temperatures will lead to higher accumulation rates over the entire ice sheet. Only in some very restricted coastal areas melting may occur, but the effect on the total mass budget will probably be very small. A study of the response of the Antarctic Ice Sheet to changing mass balance conditions predicts a 0.5% increase in ice volume after one century, again in case of a 3 K warming (Ref. 17). Converting these figures to sea level it appears that typical changes are 10 cm per century. However, the changing mass balances of the Greenland and Antarctic Ice Sheets counteract each other ! It should also be noted that natural variability in the accumulation rates may also give rise to sea-level variations of the order of 5 cm per century (Ref. 18).

Warming of the ice sheet (ii) is a very slow process. Relevant to the ice-mass discharge are the conditions in the basal ice layers. Here most of the deformation takes place. Whether sliding may occur or not also depends on the conditions of the bed. Figure 3 shows how a temperature signal travels downward in a thick ice sheet. In this particular example, the ice sheet is 2500 m thick and the accumulation rate equals 0.3 m ice depth per year. A sinusoidal temperature perturbation of magnitude 20 K was imposed to the surface during half a period (500 yr). It is obvious that it takes a long time before the basal layers feel the temperature increase. The time scale involved here is typically thousands of years.

Grounding-line instability is a more spectacular process. It is a typical example of a low probability event with dramatic consequences. Such events are most difficult to handle, both scientifically and politically.

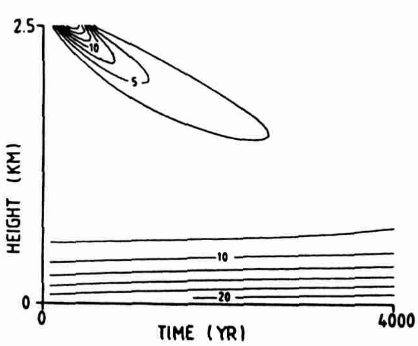

Figure 3. Downward penetration of a temperature signal. Temperature (K) is relative to undisturbed surface temperature. Ref. 19.

4. THE GROUNDING-LINE PROBLEM

The West Antarctic Ice Sheet (the irregular shaped part in the lower left corner of Figure 2) has a bed far below sea level in most places. Even if the ice would be removed and the bed would have attained a new isostatic balance, large parts would remain submerged. The West Antarctic Ice Sheet is surrounded by ice shelves , which are typically 800 to 200 m thick. The Ross and Ronne Ice Shelves, extending over hundreds of kilometers, are the most important ones. At several places these shelves run aground. A cross section of a typical configuration is shown in Figure 4.

It is likely that the so-called pinning points exert a strong influence on the stress field in the ice shelf. Upstream of the pinning points compressive stresses tend to thicken the ice and thus regulate to some extent the ice-mass discharge from the main ice sheet. If for some reason the ice shelves become thinner, the pinning points will disappear. Reduction of the compressive stress will then cause upstream thinning, and, as a consequence, the grounding line will retreat. For bed profiles like the one showed in Figure 4, it is doubtful whether a new equilibrium would be established. A total collapse of the ice sheet seems to be very well possible in this case.

There are various reasons why ice shelves could thin in case of a climatic warming. Higher ice temperature leads to larger thinning rates, but this is a very slow process. Melting at the bottom of the ice shelf is probably more important. It depends critically on how well water can be exchanged between the subshelf reservoir and the ocean, however. A figure of 1 m/yr has been suggested several times for the increase in bottom melting of the Ross Ice Shelf, but a solid base for such an estimate does not exist. Accumulation on the surface of the ice shelves will probably increase, thereby counteracting the change in melting at the bottom.

Some geological evidence exists that at the last glacial maximum (20 000 yr BP) the grounded ice extended much further into the Ross Sea, implying a grounding-line retreat of hundreds of kilometers since that time. This retreat was probably initiated by a rising sea level (about 100 m) due to melting of the Northern Hemisphere ice sheets (Ref. 20). An aspect of extreme importance to this problem concerns the state of the West Antarctic Ice Sheet in the last major interglacial.

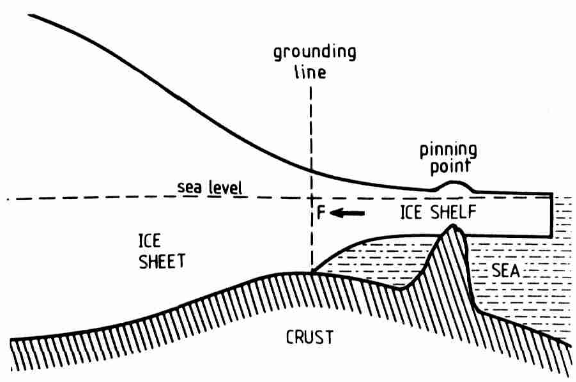

Figure 4. An ice sheet - ice shelf system typical for the West Antarctic Ice Sheet. Pinning points effect ice flow from the main sheet.

Here opinions differ widely. Mercer (Ref. 1) presents a number of arguments suggesting an ice-free West Antarctica (apart from a few glaciated islands) in that time, whereas Drewry (Ref. 21) has the opinion that the West Antarctic Ice Sheet survived the last interglacial.

Attempts have been made to clarify this point by modelling studies of different complexity (Refs. 20, 22-23). Unfortunately, this has not yet given reliable answers. Tuning models to produce grounding-line retreat can easily be done by choosing model parameters well within their range of uncertainty.

A major problem exists when it comes to the description of the stress field in the vicinity of the grounding line (i.e. in the transition zone). In the grounded ice sheet, the balance of forces is essentially between the horizontal pressure gradient and the shear stress. In the ice shelf, on the other hand, shear stresses are small and the longitudinal stress gradient balances the pressure gradient arising from the surface slope. In view of these basic differences in stress regime, it is clear that a proper description in the transition zone is not easy. A further complication arises from the highly nonlinear character of the flow law for ice.

Even if the stress field can be modelled in a satisfactory way, problems remain. Too little is known about the boundary conditions, for instance. Near the grounding line, basal sliding velocities are known to be high. However, questions like 'How critically depends sliding on basal melting and subglacial water pressure' need to be answered.

Initial conditions for model integrations also form a problem. It is not known, for instance, how the West Antarctic Ice Sheet would evolve in the absence of any climatic change. Further retreat of the grounding line could occur anyway, but it is also possible that isostatic rebound in the Ross Sea will cause further grounding of the Ross Ice Shelf in the near future. Here gravity-anomaly measurements may help, but it is difficult to interpret these in a straightforward way.

5. HOW SATELLITES MAY HELP

Images from satellites have made it possible to monitor sea ice on a global scale. Sea-ice extent is an important parameter because it is a good indicator of climatic conditions in the polar zone. It probably tells something about mixed-layer temperature in the Arctic and Antarctic regions. It is also likely that accumulation over the Antarctic Ice Sheet is closely related to the distribution of sea ice in space and time.

Another important element to monitor is the ice-shelf edge. It is known that the generally steep edges of the Ross and Ronne Ice Shelf exhibit marked variations in their position. Although it is not yet clear on which factors such variations mainly depend, progress in modelling of ice shelves will probably make interpretations possible in the near future. A better idea on the evolution of the West Antarctic Ice Sheet during the last 500 years may result.

However, most important with regard to the polar ice sheets are the slow changes in surface elevation. Radar altimetry from satellites has already proven its potential for accurate determination of the surface topography of ice sheets (Refs. 24-25), although some problems remain to be solved. In particular the grounding zones of the West Antarctic Ice Sheet should be monitored. An eventual dramatic collapse of the ice sheet will certainly be preceded by a strong 'signal' in these zones, which, interms of changes in ice thickness, may be of the order of 1 m per year. This comes close to what can be detected by radar altimetry.

Direct observation of global sea level by radar altimetry is very difficult. Changes are of the order of a few mm per year, which is much smaller than the accuracy of existing methods. The data handling required is also enormous. For a long time to come, conventional measurements of sea level will probably be more accurate.

Satellites can be very useful in the study of glacier fluctuations. In many regions glaciers are not surveyed on a regular basis. Frequent mapping based on high-resolution images would be very valuable. Snout variations are easily detected, but changes in volume are more difficult to derive. Fortunately, for a large number of glaciers, but for example not the surging-type, volume and area vary roughly in the same way.

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