Abstract. Tide gauge records indicate that a global rise in sea level has occurred over the past 80 years at a rate of about 1.5 mm yr⁻¹. Because of the poor geographical distribution of the tide gauges, this rise may be partly a consequence of a redistribution of water in the oceans without there being an increase in volume of the oceans. A principal contribution to this redistribution arises from the ongoing rebound of the crust to the melting of the Pleistocene ice sheets, a contribution that is of global significance even far from the limits of the original ice sheets. Model calculations indicate that this contribution may explain between 30 and 50% of the published estimates of the secular rise in sea level.

Introduction

Many attempts have been made to estimate the global change in sea level using tide gauge observations made over the past 80 years. Early results have been summarized by Lisitzin (1974) and more recent analyses have been published by Emery (1980), Gornitz et al. (1982) and Barnett (1983). These analyses indicate that sea level has been rising at a rate of between 10 and 30 mm per century (cm cy⁻¹) (see Table 1 of Barnett, 1983). The significance of a secular change in sea level on this time scale is primarily climatological, being a consequence of either water added to the ocean or of a change in the density of ocean water due mainly to a temperature change, but no satisfactory explanation yet exists. Other meteorological and oceanographic factors, such as variations in the annual mean atmospheric pressure and wind stress on the ocean surface, or secular changes in ocean currents, will change sea level locally and regionally but should not contribute to the eustatic sea level change if the distribution of tide gauge stations is uniform.

The problems associated with establishing a mean sea level curve are threefold; the evaluation of diverse tide gauge records, the lack of a global network of tide gauges, and the separation of sea level change from tectonic subsidence or emergence of the coastlines. These problems are well known to oceanographers and the above analyses have been carried out with various aspects of these difficulties in mind. The most satisfactory analysis published so far is the one by Barnett (1983). Barnett adopted a number of globally well-distributed sites whose sea level records are considered to be representative of the neighbouring oceanic areas; sites that are characterized by (i) high quality records for a long time interval, (ii) an absence of local perturbing factors such as exposure to fresh water currents and (iii) an absence of known tectonic movements. Nine such stations were chosen (Table 1) but of these only one lies in the southern hemisphere. As for the original Gutenberg and Fairbridge work, the sea level curve remains dominated by northern hemisphere observations. Barnett's estimated rate of the eustatic sea level rise for the past 80 years is 15 cm cy⁻¹.

The inherent assumption in establishing the eustatic sea level curve from a poorly distributed set of tide gauges is that regional secular changes in sea level are small. This assumption may not be valid for the available data set and a redistribution of ocean waters, without a change in ocean volume, can result in an apparent change in sea level without there being a change in the water volume. Several physical processes can produce this. Some are oceanographic such as long-period tides, fluctuations in ocean currents or changes in air pressure over the oceans. Other factors are externally driven. One example of this are the tides of rotational origin; the readjustment of the ocean surface to the changes in the Earth's rotation (Lambeck, 1980). Another example, considered in this paper, is the change in sea level associated with the disintegration of the late Pleistocene ice sheets. The added meltwater up to about 5000 years ago resulted in a substantial increase in sea level but the rebound of the crust, in response to the removal of the ice load and the addition of the water load, is still occurring today even if no further meltwater has been added (see the paper in Andrews, 1974; Mörner, 1980). This rebound is most evident for regions near or beneath the former ice sheets and tide gauge records at such sites are usually excluded from the analysis of the global eustatic sea level curve. But the same adjustment process occurs worldwide due largely to the added meltwater in the oceans (Lambeck and Clark, 1976) and some recent estimates for the south-west Pacific region, for example, show that the resulting relative sea level change can amount to 1 mm yr⁻¹ (Nakiboglu et al., 1983; Lambeck and Nakiboglu, 1984). This effect is not constant over the ocean since the ocean surface must remain an equipotential.

Recent Sea Level Changes Due to Crustal Rebound

The theoretical problem of quantifying sea level changes caused by the exchange of mass between ice sheets and oceans has been developed by Farrell and Clark (1976). The problem is one of finding a solution of an integral equation which
contains a model of the ice load and its melting history, a model of the planet's rheology and a model of the geometry of the oceans and continents. The solution of this equation, subject to the condition of conservation of total mass and to the requirement that the ocean surface is equipotential at all times, yields sea levels through time after the onset of melting. We use here the formulation used by Nakiboglu and Lambeck (1980) and Nakiboglu et al. (1983) and a mantle of uniform effective viscosity. This model ignores the elastic response of the lithosphere to the loading but this is unimportant for the present purpose. The adopted ice load model for the northern hemisphere is the ICE 2 model of Wu and Peltier (1983) and the Antarctic contribution is that given by Nakiboglu et al. (1983) (somewhat modified so that the centre of the melting is now near longitude 245° east). Two epochs of melting have been considered, from 18,000 to 6000 years ago and 16,000 to 6000 years ago but the subsequent results are insensitive to this choice and the former is adopted.

Model 1 is for a uniform mantle viscosity of $5 \times 10^{22}$ Pa s and model 2 is for $10^{22}$ Pa s. If a value of $10^{22}$ Pa s is adopted then present sea level changes will be negligibly small. The computed rates of change of sea level are relatively insensitive to the details of the melting history since most sites lie far from the margins of the former ice sheets. Contributions from the Arctic and Antarctic ice sheets sometimes reinforce each other (e.g. Honolulu) and sometimes cancel out (e.g. Balboa). For the southernmost stations, Sydney, the Antarctic contribution is dominant but actually less in magnitude than further north at San Francisco. An Antarctic contribution is required by the Holocene sea level data for the south-west Pacific (Lambeck and Nakiboglu, 1984) but the amount remains uncertain.

The predicted rates of change of sea level for the stations under consideration have a maximum value in excess of 40 cm cy$^{-1}$ for Baltimore (model 2) and more than 50 cm cy$^{-1}$ for San Francisco (model 2). Both these stations lie near the limits of maximum glaciation of North America and rebound is a result of both the removal of the ice and the redistribution of the meltwater over the oceans. Elsewhere the rates of change of sea level are more typically 5 cm cy$^{-1}$.

The predicted apparent eustatic sea level curve ranges from 5 cm cy$^{-1}$ (model 1) to 9 cm cy$^{-1}$ (model 2), compared with Barnett's observed amount of 15 cm cy$^{-1}$. Clearly the effects of the post glacial rebound on present day sea levels is not insignificant and the published eustatic sea level curves based on tide gauge observations may not be wholly a consequence of an increased volume of the oceans.

### Discussion

Several options exist for discussing these results. The first is to estimate both the effective viscosity and the eustatic sea level rise from the data. If the observed sea level at site $i$ ($i=1...N$) is denoted by $\xi_i^O$ and the predicted or model sea level at the same site by $\xi_i^M$ then the optimum model is the one that minimizes the quantity

$$\frac{1}{N} \left[ \left( \xi_i^O - \xi_i^M \right)^2 \right]$$

The second term inside the outer parenthesis represents the eustatic sea level curve. With the present available data this approach is premature. In particular, it would be desirable to introduce those stations where significant post glacial rebound does occur so as to give an improved determination of the viscosity, that is, to add those stations that are often rejected in analyses for eustatic sea level changes.

The above approach can perhaps be more usefully applied to the longer records of sea level change derived from submerging or emerging shorelines since early Holocene time. A comparison of such a result with the tide gauge records would be of some interest, however, in determining whether the rheology of the Earth is linear or non-linear.
A second option is to assume that the effective viscosity of the mantle is known and to interpret the difference between the observed and predicted sealevels as a measure of a change in the water volume of the oceans. Analyses of Pacific Holocene sealevels, using the same formulation, suggests that the effective viscosity lies in the range (2-6)10^19 (Nakiboglu et al., 1983; Lambeck and Nakiboglu, 1984) and such values provide an internally consistent value for the present study. For 5x10^19 the 'corrected' eustatic sealevel rise is about 10 cm cy^{-1} compared with Barnett's observed value of 15 cm cy^{-1}.

The third option is to use the rebound results as indicators of which stations to exclude from the global analyses and to use the rebound effect as a measure of the uncertainty in the sealevel rise. The sites near Baltimore and San Francisco are most affected and if these are excluded from the analysis then the sealevel rise is reduced to 12 cm cy^{-1} with an uncertainty defined as \([(\xi_m)^2/(N-1)]^{1/2} of about 5 cm.

The origin of a secular rise in sealevel remains obscure and controversial. Estimates of the present rates of ablation of the Arctic and Antarctic land-ice are extremely uncertain and no useful comparison can be made (Lambeck, 1980). Mountain glaciers may make a more significant contribution, for while the volume of these glaciers is small they are more variable. An approximate estimate of their ablation leads to a rise in sealevel of about 4-5 cm cy^{-1} (Lambeck, 1980). If adequate sealevel records exist it may be possible to deduce the centre of ongoing deglaciation by examining the discrepancies between the observed and predicted sealevels: residual sealevels would be dropping in the vicinity of the present melting centre and rising at distances about 90o away from this centre. Such an analysis requires that the viscosity be first estimated by independent means.

Ocean warming may explain the residual secular sealevel change but this evidence is also not convincing (Barnett, 1983). Possibly part of the explanation lies in secular tides of rotational origin: the readjustment of the ocean surface to the secular change in the rotation vector of the Earth. Before these contributions can be usefully discussed one more analyses of global sealevel will be required.

References


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