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The elastic response of the earth to interannual variations in Antarctic precipitation

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Abstract. Measurements of elastic displacements of the bedrock surrounding large ice sheets have been proposed as a means to detect mass changes in these ice sheets. However, accumulation of glacial mass on the ice sheets is a noisy process, subject to large spatial and temporal variations in precipitation. We simulated the response of the Antarctic continent to a stochastic model of interannual precipitation variations and found that interannual variations in the elastic response of the earth are large when compared to the long-term mean of displacements produced by an assumed average ice mass imbalance of 10%. If, as some scientists predict, Antarctic ice mass changes in the future become dramatic, the long-term signal should be large enough to be detected by a few years of geodetic measurements, despite climatic noise.

Introduction

Over the past 100 years, measurements of global sea level rise have averaged about 1.5 mm/year (Warrick and Oerlemans, 1990). Approximately 0.8 mm/yr can be explained by thermal expansion of sea water and melting of small glaciers and ice sheets. The remaining 0.7 mm/yr could be the result of depletion of the ice sheets in Antarctica and Greenland, although glaciological studies do not indicate this (Meier, 1990). Estimates of the change in glacial mass require knowledge of precipitation onto the ice sheets, and loss to the sea due to melting and calving. The balance between these two processes is difficult to determine, and recent studies rely on only a few measurements (Jacobs, 1992). As a result, the present mass flux of the large ice sheets is unconstrained. Furthermore, mass changes due to future climate change could be larger than present changes. Meier (1990) predicts an Antarctic component of sea level *lowering* of 0.3 ± 0.2 m by 2050 due to increased snowfall, a rate of 5 mm per year. Given the consequences of changes of this amplitude, the understanding and detection of future sea level rise is of social and economic significance.

It has been proposed (Hager, 1991) that mass changes in the large ice sheets could be detected by measurement of elastic crustal displacements. Indeed, recent studies (James and Ivins, 1995; Wahr et al., 1995) have confirmed that plausible long-term loading scenarios could result in vertical displacements of coastal bedrock of a few mm per year, an amplitude detectable by positioning surveys, such as Global Positioning System (GPS). Wahr et al. (1995) and James and Ivins (1995) have noted that viscoelastic movements of the crust are likely to be at least as large as the elastic response due to present-day ice mass changes. Wahr et al. (1995) have proposed that concurrent measurement of gravity could be used to remove the viscoelastic component of crustal movement.

Any positioning survey performed in the vicinity of a large ice sheet will measure the elastic response of the crust due to ice mass variations on both short and long time scales. Anthropogenic climate change could conceivably cause mass variations on a time scale of tens of years. However, large precipitation variations occur on an annual basis. As a result, the elastic response of the crust will also vary on time scales shorter than those by which gross climate change operates. If these short-term variations in displacement are of sufficient size, they could conceal displacements caused by climate-induced mass variations for several years. In this report, we discuss precipitation variations over the ice sheets and their impact upon the feasibility of detecting long-term changes in the ice sheet mass, using the Antarctic ice sheet as an example.

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Snow Accumulation in Antarctica

The average mass balance for the continent of Antarctica is given by Giovinetto and Bentley (1985) as the water equivalent of snow accumulation values. Figure 1 shows a profile of accumulation across the continent for a cross section of their data set. This profile exemplifies patterns of precipitation across the continent as a whole. Snowfall is plentiful around the perimeter of Antarctica, as storms moving inland are blocked by the steep slopes of the ice sheet, forcing the majority of their moisture to be deposited on the coast. The interior of the ice sheet receives a smaller amount of moisture through the cooling and condensation of moisture carried by poleward moving air masses (Bromwich, 1988).

These precipitation processes vary both in space and in time. Giovinetto (1964), using snow pit measurements, estimated the temporal standard deviation of annual accumulation to be 24% of the local mean value. Bromwich (1988) cites higher values in several locations. These temporal variations are given only for points within Antarctica. Larger areas have smaller variabilities due to the imperfect spatial correlation of annual

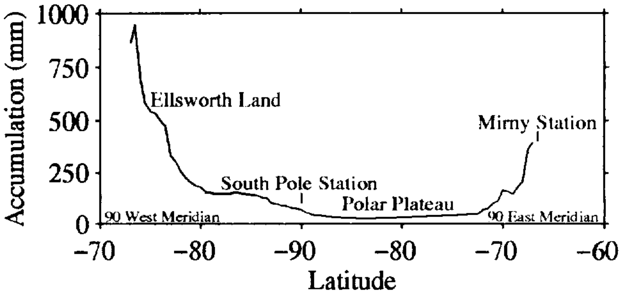

Figure 1. Profile of accumulation across Antarctica, following the 90° East and 90° West meridians, as given by *Giovinetto and Bentley*, 1985.

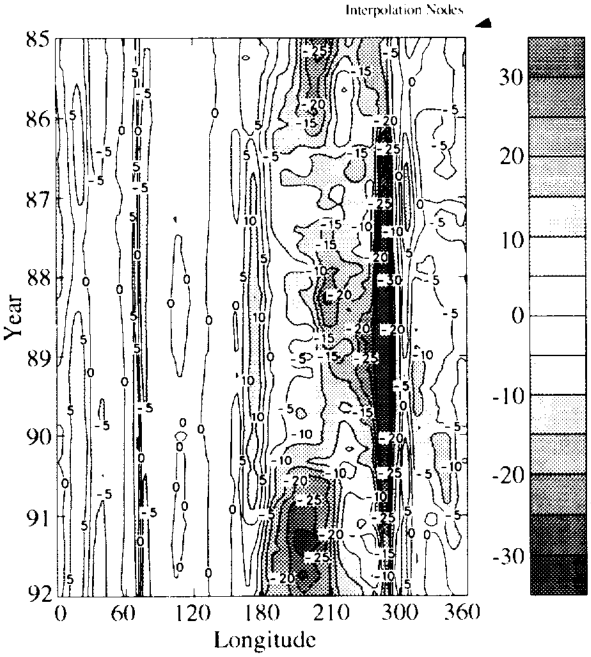

Figure 2. Time vs. longitude plot of meridional moisture transport across 70° S. Negative values indicate a southward directed moisture flux. Units are kg m^{-1} s^{-1}. The upper tick marks indicate interpolation nodes used to define the spatial variability of precipitation in the ice loading model (see text). Reproduced from *Bromwich et al.*, 1995.

precipitation anomalies between points in an areally averaged region. In general, the correlation of precipitation anomalies decreases with distance (Bromwich, 1988). The characteristic distance over which a precipitation anomaly is well correlated is as yet undetermined in Antarctica (Oerlemans, 1981).

The transport processes described above draw moisture from the southern oceans onto the continent of Antarctica. Bromwich et al. (1995) describe this process as the flux of moisture across the continental boundary. Moisture transport data from stations around the continent, though sparse, were analyzed numerically by the European Center for Medium-Range Forecasts (ECMWF) to model the advection of moisture onto the continent. Moisture flux across latitude 70° S is given as a function of longitude in Figure 2. The resulting net precipitation values were found to be close to independently measured accumulation values of 151-156 mm/a (Bromwich 1990). As a result, Bromwich et al. (1995) consider the ECMWF moisture flux model to be a reasonable one for meridional moisture transport onto the continent.

Figure 2 shows substantial spatial and temporal variation in moisture flux. At various longitudes, many anomalies persist for periods of months to years. In particular, the region between 180° and 300° E shows large variations in moisture flux. Other regions show smaller variations, but this is likely due to the fact that 70° S crosses the interior plateau in East Antarctica. This is a region of little accumulation; coastal regions can be inferred to have more precipitation, and also larger variations. In any case, it is possible to distinguish individual moisture flux variations by looking at anomalies which vary in time independently of anomalies in neighboring longitude bands. For example, the maximum between 270° and 300° E persists for over five years, while neighboring anomalies vary on shorter time scales. Other anomalies are apparent, and appear to exhibit a comparable spatial scale.

As discussed above, it appears that moisture transport anomalies in Antarctica have a characteristic width of about 30° longitude, and are likely to be fairly constant along meridians, as the direction of moisture flux into Antarctica approximately parallels meridians. Anomalies in moisture convergence, and thus mass loading of the ice sheet, do not necessarily follow the same spatial patterns as moisture transport across 70° S. However, to a rough degree, the two processes should be correlated, and to the degree of estimation with which our calculations are intended to be interpreted, this assumption will not significantly affect our results. Thus, we infer that there are roughly 12 "independently precipitating" regions in Antarctica.

An Ice Loading Model

To measure the effect of variable precipitation on crustal displacements, we developed a stochastic model of precipitation for Antarctica. The model designates 12 "independently precipitating" regions, each a sector of 30° longitude extending from the Antarctic coastline to the pole. To calculate the load, $L(\theta,\phi)$, at a point of latitude θ, and longitude ϕ between longitude values of sector midpoints ϕ_i and ϕ_{i+1}, we used:

$$L(\theta,\phi) = C\rho A(\theta,\phi)\overline{P}(\theta,\phi)\left(1+S(\theta,\phi)\right) - \rho A(\theta,\phi)P(\theta,\phi) \quad (1)$$

Here, ρ is the density of water, $A(\theta,\phi)$ is the area of a region 0.5° by 0.5° at the point (θ,ϕ), and $\overline{P}(\theta,\phi)$ is the average precipitation at this point, as given by Giovinetto and Bentley (1985). C is a simple ratio representing a fractional change in the long-term average precipitation induced by climate change. $S(\theta,\phi)$ represents the variability of precipitation:

$$S(\theta,\phi) = f(\theta)\left(\frac{(\phi_{i+1}-\phi)v_i + (\phi-\phi_i)v_{i+1}}{30°}\right) \quad (2)$$

The terms v_i and v_{i+1} are stochastic terms representing the temporal variability of precipitation in neighboring sectors denoted i and $i+1$. Following Giovinetto (1964), these terms are randomly selected from a normal distribution with standard deviation of 0.25 and mean of 1.0. The correlation between the two neighboring regions is determined by the multipliers of these stochastic terms, which linearly interpolate the two anomalies for longitude values between the midpoints of the two sectors, designated as interpolation nodes in Figure 2. The term $f(\theta)$ is used to eliminate the discontinuity at the pole by letting $f(\theta) = (90° + \theta)/10$ for $\theta < -80°$ and $f(\theta) = 1$ otherwise.

In equation (1), the first term represents the precipitation load deposited on the Antarctic ice sheets in one year, and includes a stochastic term which simulates the variability of precipitation. The second term represents the glacier outflow, assumed to be equal to the long-term mass balance of the ice sheet. Oerlemans (1981) estimated the time scale over which the Antarctic ice sheet returns to equilibrium after a fluctuation in its mass balance to be on the order of thousands of years. As our model looks at mass changes on a much shorter time scale, annual changes in the ice sheet mass should not affect the glacial outflow rate. A resolution of 0.5° by 0.5° was used for calculating the load. Precipitation falling on the ice shelves is not included in the loading model, as only the grounded regions of the ice sheets contribute to both crustal loading and sea level rise (Jacobs, 1992).

A value for the climate change term C was determined by assuming 0.5 mm of sea level rise per year, the amount unaccounted for by estimates of Warrick and Oerlemans (1990). 0.5 mm, averaged over the ocean's area, is equivalent to 14 mm averaged over the grounded portion of the Antarctic continent, or 10% of the annual mean mass balance. Thus, we used $C = 0.90$. This value represents a scenario for which the present missing sea level rise is due to decreased precipitation in Antarctica. If, as proposed by Meier (1990), sea level lowering of 5 mm/a occurs as a result of increased Antarctic precipitation, then $C = 2$ would apply. The elastic response of the earth to the applied load was calculated using Green's functions given by Farrell (1972). Vertical and horizontal displacements were calculated for each of 100 years, and the cumulative response of the crust over time was determined.

Results and Discussion

Some of the model results are given in Figure 3 as vertical displacement vs. time for a few selected points around the continent. The stochastic measurements of the displacement are compared to the displacements expected assuming no short-term precipitation variations. The difference between the two curves varies in both space and time, as governed by the spatial and temporal variability of the precipitation model. Indeed, the curves which include precipitation variability are random walks about their corresponding straight curves, which do not account for precipitation variations.

To quantify the amplitude of displacement variations resulting from precipitation anomalies, we calculated the standard deviation of annual displacement for points across Antarctica. Figure 4 shows these results for both vertical and horizontal displacements. Most of the large variations are near the coast, where total precipitation levels are greatest. The annual displacements expected without precipitation variations were also calculated and are in general a fraction of the standard deviations. In most places, the standard deviation of displacement was between 1.0 and 1.5 times greater than the mean, for both horizontal and vertical displacements.

A random walk with a standard deviation of σ for each step can be expected to deviate from its expected value over time by $\sigma\sqrt{t}$. Here, t is the number of independently varying time steps, which we have taken to correspond to the number of years of measurement. Over time scales of a few years, these deviations as a fraction of the expected values are particularly large. Thus, it is difficult to accurately relate displacement measurements taken over only a few years to long-term changes in ice sheet mass. The results of an attempt to do this can be observed in Figure 3. Slopes of the variability curves taken over time windows of about five years rarely equal the slope of the expected long-term displacement; in certain time intervals, they can even be of the wrong sign. Extrapolation of only a few years of crustal displacements over long time periods can result in faulty estimates of climate induced changes in ice sheet mass. Longer surveys, however, could recognize the trend of long-term climate change more reliably. Figure 3 shows that time intervals of about 20 years could accurately represent the long-term trend of crustal displacement.

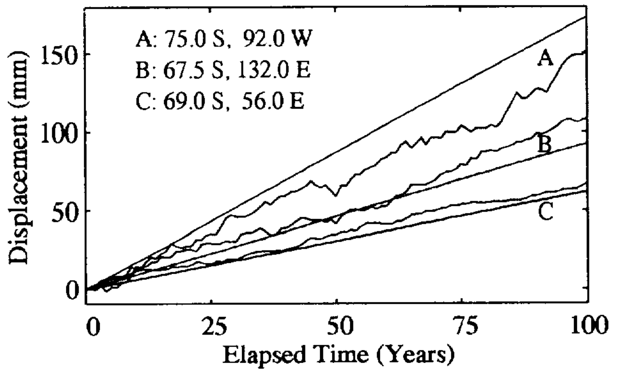

Figure 3. Vertical displacement vs. time for 100 years of simulated ice loading at three points within Antarctica. The straight lines show the expected displacements assuming 0.5 mm/a sea level rise and no precipitation variations. Neighboring rough lines give displacements for the same points as calculated with random spatial and temporal variations in precipitation. Locations of the three points are shown in Figure 4a.

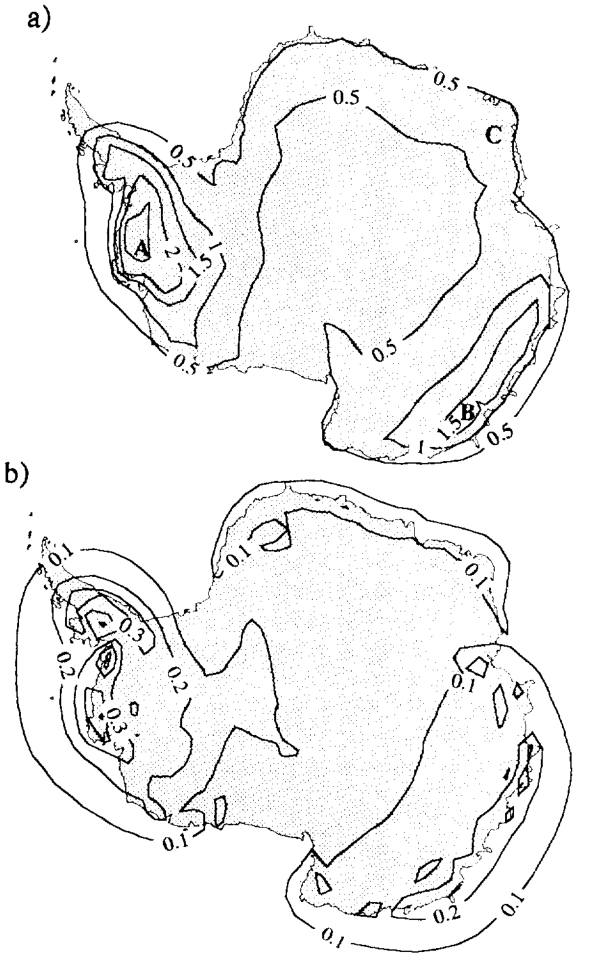

Figure 4. (4a) Standard deviation of the annual vertical displacement, as determined for 100 years of variable precipitation and 0.5 mm/a sea level rise. Plots of displacement vs. time are shown for points A-C in Figure 3. (4b) Standard deviation of the magnitude of annual horizontal displacement for the same model. For both figures, the mean annual displacement is a factor of 1.0 to 1.5 less than the standard deviations shown.

Potential future climate change of a scale proposed by Meier (1990) will be more easily recognized by crustal displacements. Although variations in precipitation are represented in this study as a percentage of the mean precipitation, a change in mean precipitation does not have a proportional affect on the resulting load. As shown in equation (1), small sec-

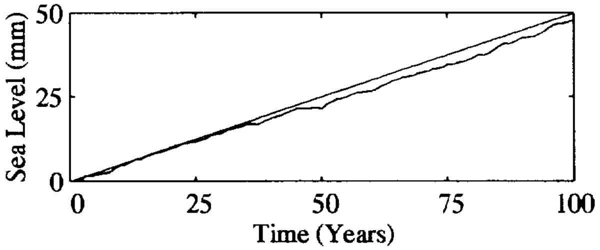

Figure 5. Cumulative sea level rise due to Antarctic ice mass changes for the loading model used to calculate displacements.

ular changes in precipitation, represented by values of C near unity, are nearly canceled by the nonvarying effect of glacial outflow. In this case, variations in displacement are large. However, when C changes dramatically, glacial outflow does not balance precipitation, and the rate of ice sheet growth is many times larger than it would be if the ice sheet were nearly in balance. Precipitation variations, however, only grow in proportion to the change in mean precipitation, and as a result become small in comparison to the long-term signal of climate change. For example, if we use a value of $C = 2$, the slopes in Figure 3 become negative, and larger by a factor of 10, as shown by the loading equation. The climatic noise term, however, only increases by a factor of 2.0/0.9, or about 2.2. Thus, the effects of precipitation variations on the observed signal become small when compared to the long-term signal of climate change. In this case, a five year study is likely to present an accurate picture of climate change in Antarctica.

Figure 5 shows the changes in sea level due to the stochastic model as compared to the long-term mean value of 0.5 mm/a. The two curves are closer together, and less noisy than the analogous curves given for displacement in Figure 3. The standard deviation of the annual change in sea level is 0.32 mm/a, a value smaller than the long-term expected value of 0.5 mm/a. Thus, the variations in sea level over time are smaller than the variations in the resulting displacements, when taken as a percentage of the average value. The difference in variability for two measurements of the same process, ice mass changes in Antarctica, is due to the high spatial variability of precipitation. Displacement measurements are the result of local precipitation anomalies, while sea level variations are the average of many such anomalies averaged over the entire continent, and are thus expected to be smaller by a factor of $\sqrt{n}$, where n is the number of independently precipitating regions (Oerlemans, 1981). Estimates of the long-term mean of accumulation over the entire ice sheet could be made in a short period of time by combining data from several locations to get a less noisy result such as Figure 5. Figure 5 was, however, made assuming that long-term changes in precipitation are constant over the entire continent. In reality, this is unlikely to be the case, given the general complexity of climate change, and the spatial heterogeneity of Antarctic weather patterns.

Conclusions

We have shown that accumulation of ice mass in Antarctica is a highly variable process and can cause large variations in both sea level rise and in the Earth's elastic response to mass accumulation. A positioning survey designed to measure crustal movements not associated with ice sheet mass changes would be affected by variations in displacement such as those shown in Figure 4. Interpretations of positioning surveys made in the vicinity of a large ice sheet should account for this climatic noise. One way of doing this is to accompany a positioning survey by measurements of local surface mass accumulation which can be done using stake networks. If, however, the goal of a survey is to measure short-term changes in the ice mass of the Antarctic ice sheets, mass accumulation or depletion measurements are in fact the aim of the survey. In this case, care must be taken in designing such a survey to provide sufficient spatial resolution to adequately account for precipitation variations. The spatial resolution of such a survey is determined by the number of "independently precipitating" regions, a number which is as yet undetermined, but roughly estimated here to be about 12 for Antarctica.

Care must be taken in the extrapolation of short-term measurements of ice sheet mass changes to mass changes induced by long-term climate change. Interannual precipitation anomalies are large enough to significantly obscure the short-term signal of climate change as observed in the past century. If, however, climate change significantly accelerates mass changes on the large ice sheets, these long-term trends could be detected in a few years by crustal displacement measurements.

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