Glaciological and climatological probabilities and improbabilities of alternative glaciation models of Antarctica

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In order to explain certain glacial and sedimentological features in the Transantarctic Mountains, two competing hypotheses have been proposed regarding the late Neogene history of the Antarctic ice sheet, which invoke fundamentally different ice sheet reconstructions. One hypothesis, the "giant ice sheet hypothesis" (Denton et al., 1984) holds that the East Antarctic ice sheet has been a relatively stable feature since at least the Miocene and that there has (have) been early phase(s) during which the Transantarctic Mountains were completely overridden by an ice sheet of considerably larger volume than anything recorded later during the Plio-Pleistocene. This enormous ice sheet would have extended to the continental break everywhere and would have led to a radial flow pattern with only one central dome. The alternative "waxing and waning" or "dwarf ice sheet hypothesis" forwarded by Webb et al. (1984) considers a smaller and much more variable East Antarctic ice sheet, which repeatedly collapsed until as recently as the mid to late Pliocene. This involved the opening of a seaway across the Pensacola and Wilkes subglacial basins, in which marine diatom deposition could take place.

Having a fairly good picture of the behaviour of the Antarctic ice sheet during the last glacial cycle and of its present-day geophysical setting, what kind of ice sheet geometries can one reasonably expect under what kind of environmental conditions, and what kind of physical mechanisms might be involved to explain the above hypotheses? In an attempt to formulate answers to these questions, experiments were performed with a high-resolution three-dimensional numerical model for the entire Antarctic ice sheet (Huybrechts, 1992). This model is fully time-dependent, considers thermomechanical coupling and freely generates the ice sheet geometry in response to changes in environmental conditions (sea level, accumulation rate and surface temperature). The model can in principle cope with any set of environmental conditions and has been thoroughly tested on the ice sheets of Antarctica and Greenland (e.g. Huybrechts, 1990; Letreguilly et al., 1991). The latter ice sheet can be considered as the modern analogue for an Antarctic ice sheet in a climate warmer by 10° to 15°C. Tests were performed covering the temperature range between -10°C and +30°C with respect to today's conditions and sea level fluctuations between the present stand and -130 m. Also topography was allowed to vary between the

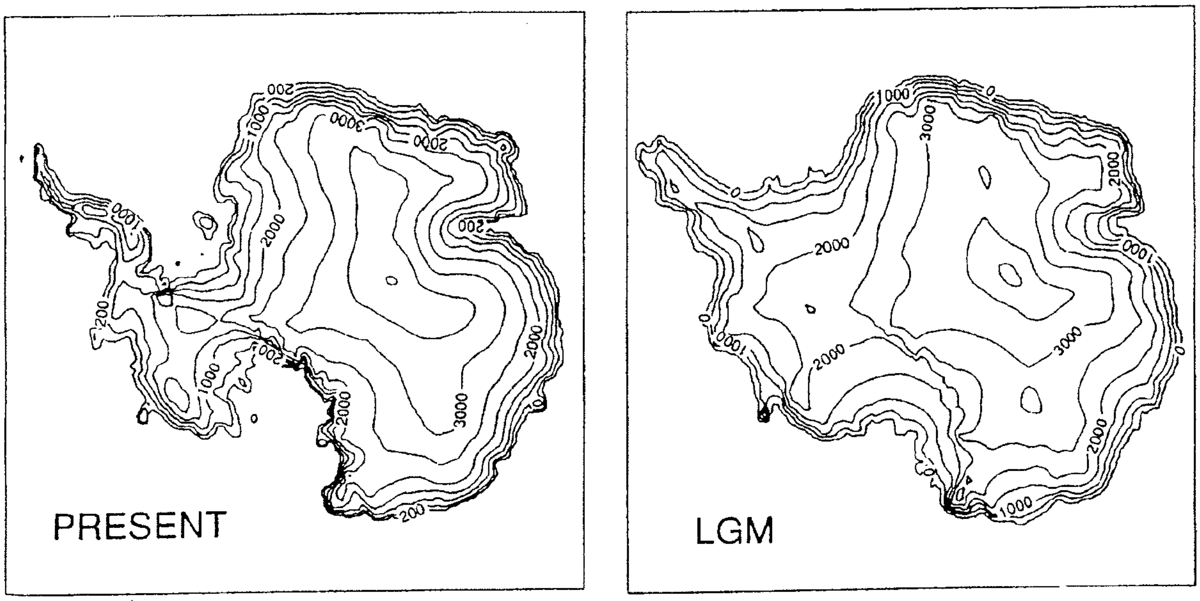

Figure 1: Reconstruction of the Antarctic ice sheet during the Last Glacial Maximum compared to the present ice sheet geometry. The right panel results from a computer simulation of the last glacial cycle with a numerical ice flow model, and takes into account transient effects and a climatic forcing derived from the Vostok ice core. Shown are surface elevations in meters above present sea level.

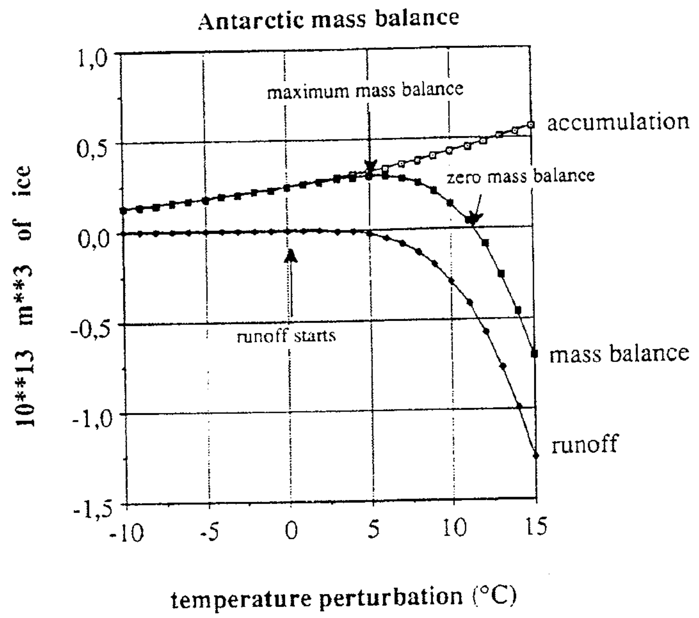

Figure 2: Dependence of the Antarctic surface mass balance on temperature relative to the present. Accumulation rates were derived as a function of the saturated vapour pressure and melting rates were calculated with a degree-day method.

present situation and an environment in which mountains were much lower, as called for by the dwarf ice sheet hypothesis.

The Antarctic ice sheet during the Pleistocene glacial cycles.

The behaviour of the Antarctic ice sheet during the Last Glacial Maximum probably provides the closest analogue for the hypothesised giant ice sheet from the recent glacial history. Results from the Vostok ice core indicate that during the LGM temperatures were about 10°C lower than today, and snow accumulation rates were about half of present values. Storage of ice on the continents of the northern hemisphere furthermore led to a eustatic sea level lowering of some 130 meters. Experiments with the ice sheet model brought to light the important role played by sea level. A lowering of the world-wide sea level stand by around 130 meters appeared to be enough to initiate the chain of dynamic reactions that ultimately caused complete grounding over the entire continental shelf. The combined effects of accumulation and temperature changes, on the other hand, turned out to imply only small changes of the ice thickness. As a consequence, surface elevations over the East Antarctic plateau were little different from today. If anything, they were even lower because of the lower accumulation rates. Unlike the giant ice sheet reconstruction by Denton et al. (1984), also the respective ice domes are well conserved during a glacial cycle (Figure 1). Transferring these findings to the postulated overriding ice sheet poses a problem. First of all, it indicates that the giant ice sheet necessarily involves the existence of a West Antarctic ice sheet with ice shelves, implying temperatures not much higher than today. In order to make the West Antarctic ice sheet expand over the continental shelf, a low global sea level is required, possibly suggesting northern hemisphere glaciation in Miocene times, for which there is otherwise no serious evidence. Both these conditions are furthermore linked with cold global conditions, which are unlikely to have produced the large precipitation amounts needed to cause massive overriding of the Transantarctic Mountains. This makes the giant ice sheet reconstruction rather hard to understand unless it is assumed that topographical and climatic conditions were entirely different from today.

Which mechanism is needed for episodal East Antarctic ice sheet destruction? In the last few decades, several instability mechanisms were suggested that could have played a role in the Antarctic glacial history, namely the marine ice sheet instability, creep instability and large-scale surging. In my opinion, none of these instability mechanisms is a likely candidate to have caused the kind of East Antarctic ice sheet geometries necessary to explain the waxing and waning/ dwarf ice sheet hypothesis.

The marine ice sheet instability holds that the stability of an ice sheet grounded below sea level crucially depends on its surrounding ice shelves, which are believed to keep the grounded ice sheet in place. Any

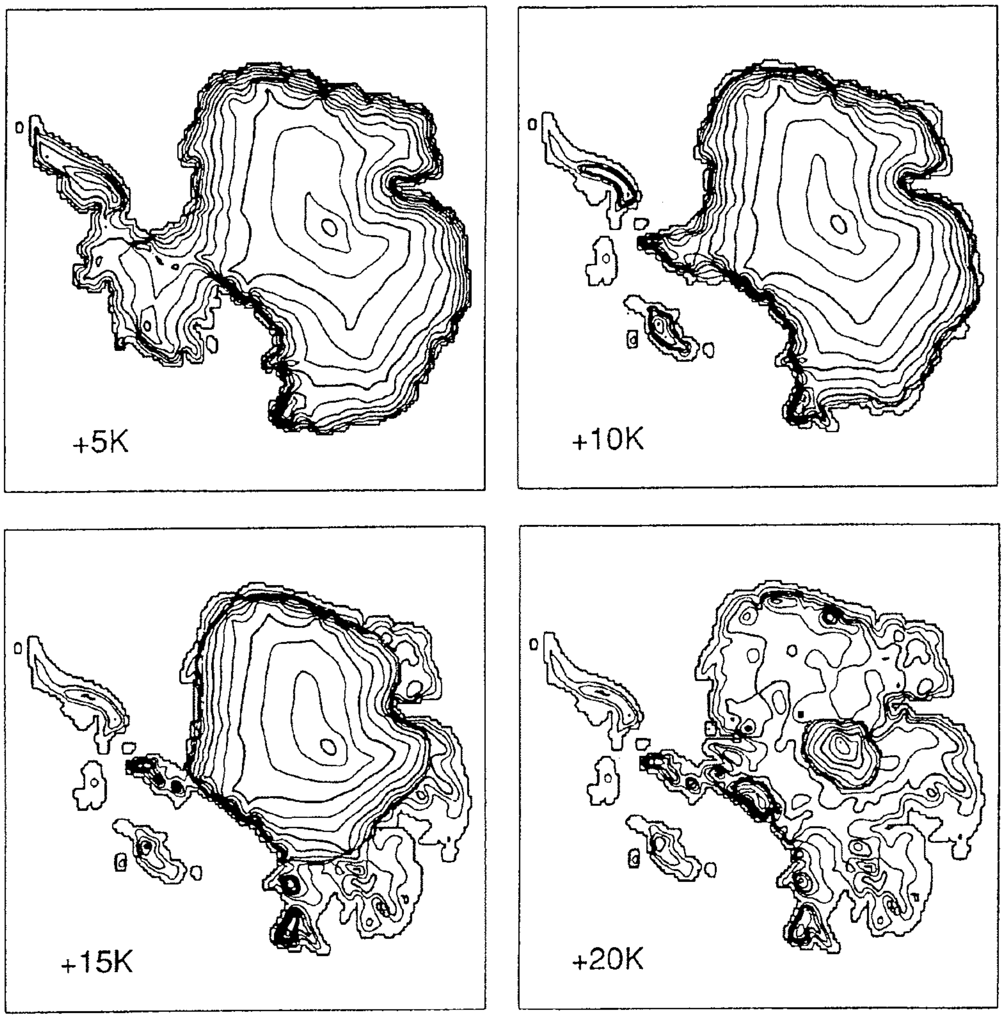

Figure 3: Steady state ice sheet geometries for temperature perturbations above present levels as indicated. Isolines are for surface elevation. Contour interval is 333 meter, the thick lines are for every 1000 meters.

weakening of these ice shelves would then under certain circumstances lead to a run-away process in which the entire marine ice sheet collapses. This mechanism has received a lot of attention with regard to the West Antarctic ice sheet, though the effectiveness of this mechanism remains the subject of considerable debate. Also all conditions required for this mechanism do not seem to be fulfilled in East Antarctica, which is only truly marine-based in a relatively small area and does not have the typical inward sloping bed topography.

Two other mechanisms, creep instability and surging, call on the thermodynamics of polar ice sheets. Creep instability may result from the feedback between ice temperature and ice velocity: the warmer the ice, the more easily it deforms and the more shear heating is produced, which in turn leads to higher temperatures and so forth. This could initiate an explosive shear heating instability, followed by a massive surge. However, this instability appears to be a model artefact rather than a realistic feature because of the neglect of horizontal heat advection in early studies, so that a basic damping mechanism was excluded.

Water and/or water-soaked sediment lubrication could in principle lead to surging behaviour, though much will also depend on the details of the basal hydraulics and on how effective basal water is removed. However, it is doubtful whether the East Antarctic ice sheet could have exhibited surging behaviour, one reason being that the base is unlikely to have reached the pressure melting point over a sufficiently large area. Model experiments show the difficulty of raising the basal temperature to the melting point, since a warmer surface climate over Antarctica will in general also lead to higher accumulation rates, in turn inducing a cooling because of increased advection of cold ice towards the basal layers. Also, these instability mechanisms could at best explain a periodic thinning of the ice sheet, and not the removal of large parts of the ice sheet, which would still have to be melted down from the surface.

This leaves the regular mechanism of interaction with the environment, namely via

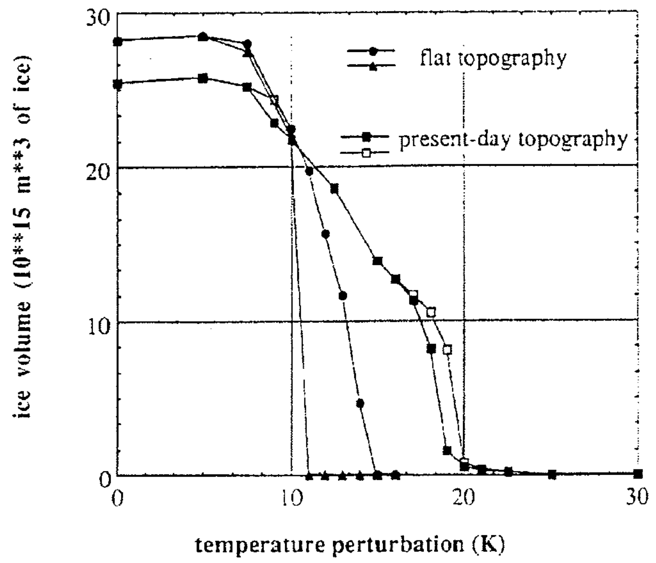

Figure 4: Solution diagram giving the steady state ice volumes as a function of the temperature perturbation. The full squares and full triangles are for model runs in which the initial condition was an ice-free continent, the open squares and closed circles started from the present ice sheet. Regions with multiple solutions indicate that the resulting ice sheet geometry depends on its past history.

the surface mass balance, as the only credible alternative.

At present, air temperatures are so low - they remain largely below freezing even during the summer - that there is hardly any surface melting or runoff.

Because air temperature is the main limiting factor for accumulation as colder air can carry less precipitable moisture, the mass balance will be even higher than today for a moderate warming of up to some 5°C, and become only negative for temperature rises of more than 11°C (Figure 2). This does not necessarily mean that the Antarctic ice sheet will disappear for larger temperature rises. In general, the ice sheet will start to shrink and try to reorganize its height-elevation distribution so as to make the accumulation area larger with respect to the ablation area.

The Antarctic ice sheet in warmer climates

Figure 3 shows the resulting ice sheet geometries in a number of experiments, in which temperatures were progressively raised above present levels. It was found that a temperature rise of between 9 and 10°C is required to destroy the West Antarctic ice sheet. This happens when the surface balance becomes negative at sea level and grounded ice is no longer able to feed an ice shelf.

For the temperature range of up to +10°C , also East Antarctic elevations tend to rise a little because of higher snowfall rates, although the effect is not very pronounced. The Antarctic ice sheet reaches its maximum volume for a warming of +5°C. Serious retreat is only produced for temperature rises above +15°C, when local ice caps appear in Victoria Land and the Ellsworth Mountains which are uncoupled from the main ice sheet.

An interesting result was also that a split up of the ice sheet in two parts, with an ice-free corridor in between centred over the Pensacola and Wilkes basins, is only produced in the final stages, when the ice sheet as a whole has almost entirely disappeared.

The ice sheet then disappears completely from the Gamburtsev Mountains for a temperature rise of more than +25°C.

According to these model results, it thus appears that for the East Antarctic ice sheet to recede from the Pensacola and Wilkes basins a climatic warming of the order of 20°C above present interglacial levels is required.

This certainly constitutes a major climatic event of global significance.

So, in order to accept a Pliocene age for an East Antarctic ice sheet meltdown, one would have to be able to produce other independent evidence indicative of a climatic warming of such a magnitude during that time.

Further experiments, however, brought to light the important role played by topography. In model runs, in which the unloaded topography was flattened out to elevations below 500 meters, it was found that the ice sheet already disappeared for temperature rises of +15°C.

Also the basal area at the pressure melting point was much larger, basically because of the absence of relatively shallow ice above the subglacial mountain ranges.

Concluding remark

As a final remark, it seems that rapid uplift of the Transantarctic Mountains and thus much lower elevations before a few million years may well be a missing link to make both overriding of the Transantarctic Mountains and partial deglaciation of the East Antarctic continent more realistic. Overriding certainly becomes more plausible if the Transantarctic Mountains were less elevated, implying a less extensive and thinner East Antarctic ice sheet. In the limit, the presence of the West Antarctic ice sheet may not even be required to override the highest mountain tops, so that overriding may have been produced with temperatures up to 10 to 15°C higher than today. This could then also have produced much larger accumulation rates, not only because of temperature, but also because of a nearer moisture source due to a less extensive sea-ice cover and more open water around the continent. As shown on Figure 4, in the absence of an elevated topography, both the large and small ice sheet states are separated by some 5°C only, possibly implying that these states could have occurred as subsequent stages of a periodic evolution more than once, even during the more recent glacial history.

References

Denton, G.H., Prentice, M.L., Kellogg, D.E., Kellogg, T.B., 1984: Late Tertiary history of the Antarctic Ice Sheet: Evidence from the Dry Valleys - Geology, 12, p. 263-267.

Huybrechts, Ph., 1990: A 3-D model for the Antarctic ice sheet: a sensitivity study on the glacial-interglacial contrast - Climate Dynamics, 5, p. 79-92.

Huybrechts, Ph., 1992: The Antarctic ice sheet and environmental change: a three-dimensional modelling study - Ph.D thesis, Berichte zur Polarforschung, 99, 241 pp.

Letreguilly, A., Reeh, N., Huybrechts, Ph., 1991: The Greenland ice sheet through the last glacial-interglacial cycle - Palaeogeography, Palaeoecology & Palaeoclimatology (Global and Planetary Change section), 90, p. 385-394.

Webb, P.-N., Harwood, D.M., McKelvey, B.C., Mercer, J.H., Stott, L.D., 1984: Cenozoic marine sedimentation and ice volume variation on the East Antarctic craton - Geology, 12, p. 287-291.