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West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

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If the global consumption of fossil fuels continues to grow at its present rate, atmospheric CO_2 content will double in about 50 years. Climatic models suggest that the resultant greenhouse-warming effect will be greatly magnified in high latitudes. The computed temperature rise at lat 80° S could start rapid deglaciation of West Antarctica, leading to a 5 m rise in sea level.

ATMOSPHERIC carbon dioxide traps some of the long-wave radiation emitted by the Earth's surface (principally near 15 μm wavelength), thereby tending to warm the troposphere. This so-called greenhouse effect has long been suspected[1,2] but only recently, as the implications of a continuation of the current near-exponential growth of industrial CO_2 production have been realised, have many come to fear a disastrous climatic warming in the rather near future. In a recent report on the climatic effects of energy production, Revelle *et al.*[3] conclude that industrial civilisation may soon have to decide whether or not to make the tremendous investment of capital and effort needed to change over from fossil fuels to other sources of energy. Bolin[4], in hearings before the U.S. House of Representatives, points out that if all reserves of fossil fuel that are accessible by present techniques were burnt, thereby increasing atmospheric CO_2 content between five- and eightfold above its preindustrial level, the result would almost certainly be climatic disaster.

I contend that a major disaster—a rapid 5 m rise in sea level, caused by deglaciation of West Antarctica—may be imminent or in progress after atmospheric CO_2 content has only doubled. This concentration of CO_2 will be reached within about 50 years if fossil fuel continues to be consumed at its recent accelerating rate, or within about 200 years if consumption is held constant at today's level[4,5]. Keeling and Bacastow[6] believe that even if a policy of conversion to other sources of energy was started today and vigorously pursued, the global rate of consumption of fossil fuels would still double by the end of this century. If so, the actual doubling time for atmospheric CO_2 content is likely to be nearer 50 than 200 years.

Many attempts have been made to estimate by climatic modelling the average global rise in temperature that would result from a doubling of atmosphere CO_2 content. The figures obtained have ranged from 0.7 K to 9.6 K, and Schneider[7] has critically examined the models in an attempt to clear up the confusion created by these widely different estimates. He points out that some of the models give unrealistic results because they compute an equilibrium condition for the Earth's surface rather than for the Earth–atmosphere system as a whole. He stresses the advantages of radiative–convective models, which take into account vertical motions of the atmosphere and latent heat transport, and he compares the radiative–convective models of Rasool and Schneider[8], who had computed an average global temperature rise of 0.8 K, with that of Manabe and Wetherald[9] who had computed a rise of 2.3 K, later revising this to 2.9 K. He estimates that, using the most refined input of feedback mechanisms that is possible with present knowledge, globally-averaged temperatures would rise about 1.9 K. But, because some feedback mechanisms may have been improperly modelled, some (especially those involving changes in cloud cover and cloud top elevation) have been largely ignored because of our inability to do otherwise, and others perhaps remain unknown, he concludes that the best state of the art, order of magnitude estimate is that a doubling of atmospheric CO_2 content would raise average global temperature by 1.5–3 K. He believes that this estimate is as likely to be too low as too high.

More recently Augustsson and Ramanathan[10], using a different modelling technique, and taking into account the previously ignored effect of bands of weak absorption by CO_2, have calculated that global temperatures would rise about 2 K. This, they note, is similar to Schneider's figure; they find this encouraging, but surprising and perhaps fortuitous because substantially different modelling techniques were used. Their one-dimensional model gives no information about differences between latitudinal zones, but the three-dimensional model of

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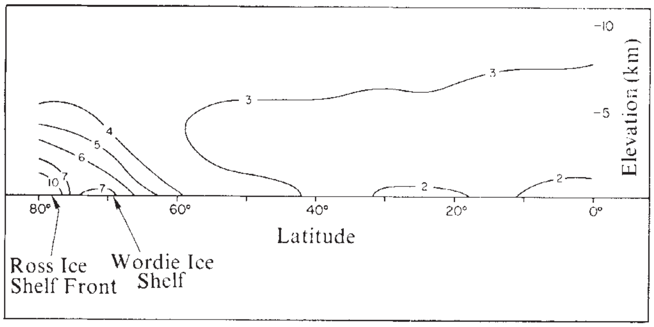


Fig. 1 Computed rise in mean atmospheric temperature, as a function of latitude and elevation, that would result from a doubling of atmospheric CO_2 content (after Manabe and Wetherald[9] who emphasise that, because of the various simplifications of the model, the quantitative aspects of the results should not be taken too seriously).

Manabe and Wetherald[9] shows greatly magnified warming in high latitudes caused by the lack of vertical mixing, and by the feedback effect of decreased albedo as snow and sea ice cover recede: temperatures would rise by $\sim$ 2 K between the equator and lat 30° north or south, by 4 K at lat 60°, by 7 K at lat 70°, and by > 10 K at lat 80° (Fig. 1). Schneider[7] agrees that this effect is likely and points out that warming in the polar regions could be crucial because of their sensitivity to changes in the energy balance.

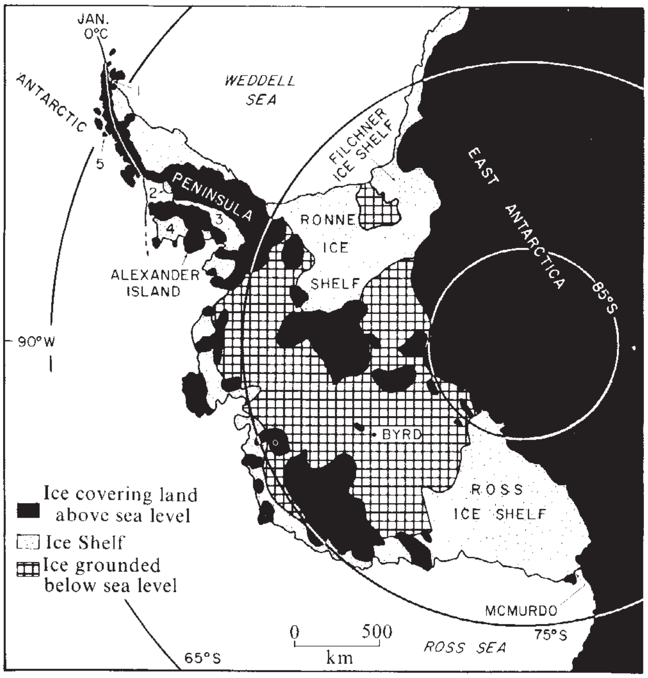
Manabe and Wetherald[9] emphasise that because their model is highly simplified—it has idealised global topography, fixed cloudiness, no heat transport by ocean currents and no seasonal variability these figures for the rise in temperature should not be taken at their face value. Smagorinsky[11] discusses the model and points out that seasonal variability is of fundamental importance in high latitudes because it determines the extent of snow and ice cover; if this factor, and the reactions of the oceans and clouds were taken into account, a very different result might be obtained; it is even possible that global cooling would be indicated. Keeling and Bacastow[6] conclude that until the feedback effect of the slow response of subsurface ocean waters can be correctly modelled, the regional climatic changes that are of greatest interest to mankind will be hard to predict. Nevertheless, as Bolin[1] points out, although the model of Manabe and Wetherald has serious shortcomings it is the most advanced that has yet been developed, and to gamble with the Earth's climate by ignoring it would be highly irresponsible. In the same vein Schneider[12] sums up the dilemma facing mankind: despite the crudities and inadequacies of present techniques for modelling the climatic effects of increasing atmospheric CO_2 content and the resultant doubts about the magnitude of the warming that would actually occur, we cannot afford to let the atmosphere carry out the experiment before taking action because if the results confirm the prognosis, and we should know one way or the other by the end of the century, it will be too late to remedy the situation on account of the long residence time of CO_2 in the atmosphere (Keeling and Bacastow[6] estimate that, if all accessible fossil fuels were burnt, restoration of pre-industrial levels of CO_2 would take at least 10,000 yr).

Is the CO_2 greenhouse effect detectable in recent climatic trends?

Since about 1940, temperatures over much of the Northern Hemisphere have dropped despite rising atmospheric CO_2 content. Broecker[13] suggests that this may have lulled us into a sense of false security about the danger of increasing CO_2 levels; the cooling does not disprove or cast doubt on the CO_2 greenhouse-warming theory but is, he suspects, merely the effect of a natural cooling cycle that has overwhelmed the warming due to CO_2, which he estimates has amounted to no more than 0.2 °C for the past 30 years. He believes that the quasi-cyclical pattern of climatic fluctuations in the recent past, which is shown by the oxygen isotope record from the Greenland Ice Sheet[14], implies that this cooling will soon level out, to be followed by a period of rapid warming as the natural climatic trend is reinforced by the effects of increasing atmospheric CO_2. In fact, the cooling since 1940 seems to have been mainly confined to middle and high latitudes in the Northern Hemisphere, and some investigators believe that the southern part of the Southern Hemisphere has warmed during the same interval. Damon and Kunen[15] have studied climatic records from 67 Southern Hemisphere stations that meet certain specifications and that have records that go back to 1954 or earlier. They find that since 1943 temperatures have changed little between the equator and lat 45° S, except in Australia and New Zealand which, as other workers also point out[16,17], have warmed by about 1° C since the 1940s. South of lat 45° S, however, they conclude that average annual temperatures increased between the 1960–64 and 1970–74 pentads, particularly in West Antarctica where they rose about 2° C at Argentine Island (lat 65° S), McMurdo (lat 78° S), and Byrd (lat 80° S) (Fig 2). Thomas'[18,19] observation that temperatures at 10 m depth in the eastern part of the Ross Ice Shelf rose about 1° C between 1958 and 1972 confirms the warming trend in West Antarctica.

Damon and Kunen[15] suggest that the climate of the Southern Hemisphere is now responding to the CO_2 greenhouse effect, whereas in the Northern Hemisphere this has recently been overwhelmed by cooling caused by man-made particulate pollution and also, possibly, from greater volcanic activity. Budd[19], however, while noting the recent warming in West Antarctica, finds no clear evidence that Antarctica as a whole either warmed or cooled between 1958 and 1972; furthermore, at the South Pole 1976 was the coldest year since records began there in 1957[20]. So far, apparently, despite recent regional warming over Australasia and West Antarctica, there is no unequivocal evidence for a global rise in temperature caused by increasing atmospheric CO_2 content. If Broecker's estimate is correct that average global CO_2-caused warming would have amounted to no more than a fifth of a degree in the past 30 years, this is perhaps not surprising.

Fig. 2 West Antarctica, showing ice shelves, ice grounded below sea level, ice covering land above sea level, and position of the 0 °C January isotherm in the Antarctic Peninsula (based on information up to the year 1962)[35]. 1, Prince Gustav Channel; 2, Wordie Ice Shelf; 3, George VI Sound; 4, Wilkins Sound; 5, Argentine Island.



First disastrous consequence of rising CO_2 levels

Those who are most aware of the climatic dangers of increasing atmospheric CO_2 do not seem to view deglaciation in Antarctica as an immediate threat. For example, Schneider and Dickinson[21], and Bolin[4], believe that the Antarctic Ice Sheet will respond to climatic warming very slowly, during millennia, while Rotty and Budyko[22,23] are more concerned with the shrinkage and eventual disappearance of the Arctic sea ice. Revelle *et al.*[3] conclude that our present understanding of the Antarctic Ice Sheet is insufficient for us to forecast how it would be affected by global warming of several degrees. They believe that the direct effect of the warming would be minimal, but suggest that increased snowfall might eventually thicken the ice sheet enough to cause surging, perhaps resulting in deglaciation of West Antarctica. But, not only would effective thickening of the ice sheet require a long interval of increased snowfall, but also it is doubtful that a thickening ice sheet would surge. I believe that Revelle *et al.*[3] underestimate the direct effect of moderate Antarctic warming, which would be likely to cause deglaciation of West Antarctica long before any significant thickening of the ice sheet could occur.

If present trends in fossil fuel consumption continue, and if the greenhouse warming effect of the resultant increasing atmospheric CO_2 is as great as the most advanced current models suggest, a critical level of warmth will have been passed in high southern latitudes 50 years from now, and deglaciation of West Antarctica will be imminent or in progress. Deglaciation would probably be rapid once it had started, and when complete would have led to a rise in sea level of about 5 m along most coasts. The reasons for this ominous situation lie in the unique characteristics of the West Antarctic ice sheet.

West Antarctic ice sheet's vulnerability to climatic warming

The Antarctic Ice Sheet consists of two unequal parts, with different histories and characteristics: the vast, long-established, mainly land-based ice sheet in East Antarctica, and the younger, much smaller marine ice sheet[24], grounded as much as 2,500 m below sea level in West Antarctica (Figs 2 and 3). Melting of the East Antarctic ice sheet would raise sea level by about 50 m, whereas melting of the West Antarctic ice sheet, much of which is only displacing ocean water, would raise sea level by no more than about 5 m on average[25] (Clark & Lingle[26] show that the sea level change would not be globally uniform).

When the Antarctic Ice Sheet formed while temperatures dropped during the late Cainozoic, there was an interval, during which temperatures dropped further, between the emplacement of the East Antarctic ice sheet in the late Miocene[27] and of the West Antarctic ice sheet, probably during the latest Miocene or earliest Pliocene[28]. This was because the land-based East Antarctic ice sheet could form as a temperate glacier, whereas the marine West Antarctic ice sheet had to consist of cold ice from the start[25]. (The thermal requirements of the West Antarctic ice sheet are discussed in more detail later.) Thus, in order to survive, the West Antarctic ice sheet needs colder summers—perhaps as much as 10 °C colder—than does the East Antarctic ice sheet, and is, therefore, more vulnerable to a rise in temperature. During sustained climatic warming, the Miocene–Pliocene sequence of glacial buildup would be reversed, and the West Antarctic ice sheet would be eliminated before the East Antarctic ice sheet was greatly affected. Fortunately, serious depletion of the East Antarctic ice sheet is a distant threat because, being land-based, it could retain a positive mass balance after climatic warming had converted it from a cold to a temperate glacier at low elevations. Even if further warming gave it a severely negative mass balance, it would waste away only slowly over millennia, by *in situ* melting, as the Laurentide Ice Sheet did 14–8,000 yr ago[29]. The resultant rise in sea level would cause considerable inconvenience, but would be gradual enough to allow coastal communities to adjust. This is apparently the type of deglaciation that Schneider and Dickinson[21] and Bolin[4] had in mind when they considered the effects of climatic warming on polar ice sheets; unfortunately, however, the West Antarctic ice sheet would be unlikely to shrink in this manner.

In contrast to the land-based East Antarctic ice sheet, the marine ice sheet in West Antarctica can exist only so long as its grounded portion is buttressed by fringing ice shelves; in particular, by the Ross and Filchner–Ronne ice shelves (Fig. 2). Thus any environmental change that diminished or destroyed these ice shelves would also diminish or destroy the ice grounded below sea level; as the ice shelf fronts receded southward, their grounding lines would also recede and the grounded ice sheet would shrink and thin. Eventually, after all ice shelves had disappeared, ice cover would be confined to areas above sea level, and glaciers would terminate in ice cliffs between high and low water levels[25,30–32].

Ice shelves are vulnerable to both oceanic and atmospheric warming. They will melt at the base if the water they are in contact with is above its freezing point; as Robin[34] notes, they are absent from the coasts of the Antarctic Peninsula only where sea temperatures rise above −1.5 °C during the warmest month. (For water with 35‰ salinity, freezing point is about −1.9 °C at the surface and about −2.2 °C at 500 m depth[33]). Melting will accelerate if a positive temperature gradient develops between the base and the surface; this will happen only if the ice shelf becomes temperate as rising air temperatures produce enough meltwater to percolate downwards and destroy the previous winter's cold wave. In fact temperate ice shelves do not seem to exist in nature, except possibly as short-lived features during climatic warming; Robin and Adie[31] observe that all known ice shelves are cold, that is, below the pressure melting point at depth, and that their northern limit on the west coast of the Antarctic Peninsula lies a short distance south of the northermost land glaciers that are cold at sea level. They conclude that a climatic warming above a critical level would remove all ice shelves and, consequently, all ice grounded below sea level, resulting in the deglaciation of most of West Antarctica.

The observations of Robin and Adie imply that where summers are warm enough to destroy the previous winter's cold wave in a glacier at sea level, ice shelves will be absent. In the Antarctic Peninsula the 0 °C isotherm for the warmest month (January), which trends south-west from the tip of the peninsula towards Alexander Island[35] (Fig. 2), is almost parallel to, and a short distance outside, the northern limit of ice shelves. Other aspects of the summer climate besides air temperature, particularly the duration and intensity of solar radiation, must also be involved in determining the northern limit of cold ice at sea level, and thus of the ice shelves, but the 0 °C isotherm for midsummer air temperature seems at least as realistic a climatic boundary for ice shelves as does, for example, the 10 °C midsummer isotherm that approximately marks the northern limit of trees[36]. Most ice shelves, however, terminate considerably south of the 0 °C midsummer isotherm. Around the coasts of East Antarctica they are limited by the positions of the outermost lateral anchor points[37], but in West Antarctica neither high temperatures nor lack of anchor points prevent the northward expansion of the Ross and Filchner–Ronne ice shelves. The frontal positions of these large ice shelves depend mainly on the position of the grounding line of the West Antarctic ice sheet, and this is determined by water depth and, to a smaller extent, by snow accumulation rates.

Average midsummer air temperatures at the fronts of both the Ross and Filchner–Ronne ice shelves are now about 4 °C to −5 °C[35]. Thus the deglaciation of West Antarctica that Robin and Adie[31] foresaw would result from sufficient climatic warming would be unlikely to start until air temperatures had risen about 5 °C, bringing summer temperatures

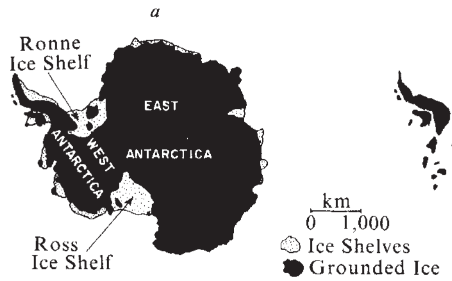


Fig. 3 *a*, Antarctic ice cover today, and *b*, after a 5–10 °C warming.

over the Ross and Filchner–Ronne ice shelves up to those now prevailing in the northwestern Antarctic Peninsula. Once this level of comparative warmth had been reached, deglaciation would probably be rapid, perhaps catastrophically so, because even a small additional rise in temperature would affect a large expanse of gently sloping ice shelf. As Hughes[32] graphically describes it, "a relatively minor climatic fluctuation along the ice shelf calving barrier can unleash dynamic processes independent of climate that cause calving bays to remorselessly carve out the living heart of a marine ice sheet." An example of deglaciation by the calving bay mechanism was the extremely rapid disintegration of the central portion of the Laurentide Ice Sheet, centred over the present Hudson Bay, sometime between 8,000 and 7,500 BP, after thousands of years of slow recession on land[38].

The Ross and Filchner–Ronne ice shelves would probably be on the verge of receding southward if summer temperatures rose 5 °C at lat 80° S. The climatic model of Manabe and Wetherald[9], for which year-round climatic uniformity is assumed, suggests a warming of more than 10 °C at lat 80° S after atmospheric CO_2 content has doubled; this concentration will perhaps be reached within 50 years. If this model is even approximately correct, rather drastic deglaciation should then be in progress in West Antarctica.

One warning sign that a dangerous warming is beginning in Antarctica will be the breakup of ice shelves in the Antarctic Peninsula just south of the recent January 0 °C isotherm; the ice shelf in Prince Gustav Channel on the east side of the peninsula, and the Wordie Ice Shelf, the ice shelf in George VI Sound, and the ice shelf in Wilkins Sound on the west side (Fig. 2). There is some evidence, not yet conclusive, that such a southward recession of the ice shelf limit in the Antarctic Peninsula has already begun; a comparison of LANDSAT imagery with earlier surveys has shown that between 1966 and 1974 nearly 600 km^2 or about one quarter of the Wordie Ice Shelf broke away, and the ice shelf in George VI Sound receded[39].

Fall in sea level by glacial growth

High latitude warming might well bring increased snowfall to Antarctica and perhaps to parts of Greenland also, as Revelle *et al.*[3] suggest. This is far from certain, however, because although the warmer air masses could hold more moisture, cyclonic disturbances might decrease in number and intensity if, as present models indicate, the latitudinal temperature gradient decreased. To what extent deglaciation in West Antarctica would be offset by glacial buildup elsewhere is hard to estimate. Robin and Adie[31] calculate that doubling the net annual accumulation rate on the East Antarctic ice sheet, which already reaches the coast, would increase its volume by no more than 10%. This, they estimate, would eventually result in a 4 m drop in sea level; however, they also conclude that the East Antarctic ice sheet would take several thousand years to reach its new equilibrium volume. Thus, if temperatures rose no further, warmth-induced deglaciation of West Antarctica might eventually be partially or even wholly offset by thickening of the surviving ice sheets. It would be unwise, however, to rely on this buildup being rapid enough to avert a disastrous rise in sea level, and in any case, if temperatures continued to rise because of increasing atmospheric CO_2 content, glacial growth in East Antarctica would eventually cease.

Previous destruction of the West Antarctic ice sheet

Considerable evidence from the Southern Hemisphere suggests that the warmest part of the last interglacial (Sangamon–Eem) was warmer than the present interglacial has been so far; for instance, subantarctic seas were then warmer than they have been since (J. D. Hays, personal communication), and in Southern Chile chemical weathering was unusually intense[40]. This warm interval—substage 5e, according to the sequence established by Emiliani[41]—was centred 120–125,000 yr ago[42]. If the West Antarctic ice sheet was absent at that time, the hypothesis that a rather moderate rise in temperature would destroy it would be strengthened.

I earlier suggested that the high sea level of the last interglacial (probably about + 6 m) resulted mainly from deglaciation of West Antarctica when temperatures there rose too high for the survival of ice shelves[28]. Deglaciation of West Antarctica alone would add a layer of water about 5 m deep over the area of the present world ocean. Later, Emiliani suggested that the high sea level resulted from deglaciation of Greenland, with minimal contribution from Antarctica, but this is highly unlikely because the marine West Antarctic ice sheet is much more vulnerable to climatic warming than is the land-based Greenland ice sheet.[43,44].

A rise in eustatic sea level is not necessarily a glacio–eustatic rise, so that the high sea level of the last interglacial by no means proves that less ice was then present. Supporting evidence for the hypothesis came later when oxygen isotopic analyses of Core V 28-238 from the equatorial Pacific showed that the mass of the oceans during substage 5e was greater than it is today[42]. The isotopic difference between the Holocene and substage 5e was about what might be expected from melting of the West Antarctic ice sheet during substage 5e. Shackleton (personal communication) now believes that because planktic and not benthic foraminifera were analysed for substage 5e in Core V28-238, the isotopic composition may include a temperature effect. Thus, although the oceans did contain more water during substage 5e than they do now, just how much more is uncertain. Measurements being made on other deep sea cores should give more accurate figures in the near future.

Possible disintegration of West Antarctic ice sheet from non-climatic causes

Some workers[45-49] believe that the West Antarctic ice sheet shrank at the end of the last glaciation when its grounding line receded as the result of the ~ 120 m eustatic rise in sea level. Others[50,51], however, believe that changes in the extent and thickness of the West Antarctic ice sheet since the last glacial age have been minor. In any case, with the larger Northern Hemisphere ice sheets gone, no further major shrinkage of the West Antarctic ice sheet as the result of rising sea level will occur in the near future.

Thomas and Weertman[52,53] believe that the present West Antarctic ice sheet is inherently unstable and that, if it disintegrates, it will do so through mechanisms unconnected with climate. Hughes[54] agrees that such internal instability mechanisms are possible and could result in surges, but he also stresses the vulnerability of the ice sheet to climatic change. Weertman[53] suggests that the presence of ice streams draining the ice sheet is a premonition of a large-scale surge, the start of a process that may cause the West Antarctic ice sheet to discharge one third to one half of its volume into the oceans over, say, 100 years. The only occasion, however, during the last half million years or so that the oxygen isotopic composition of the oceans implies the presence of less land ice than today is during substage 5e (ref. 42); that is, during an interval that was warmer than the Holocene. This strongly suggests cause and effect: the West Antarctic ice sheet was absent because of the high temperature. There is no evidence that the ice sheet has ever been seriously depleted by surges in the past and therefore, I believe, there is no reason to suppose that it will be in the future. Weertman may be right for the wrong reasons; the ice sheet is likely to disintegrate in the rather near future, but because of man-made climatic warming, not through surges resulting from internal instability mechanisms.

Conclusions

The present West Antarctic ice sheet is reasonably secure against all instability mechanisms except for climatic warming above a critical and—for the Pleistocene—exceptional level. In the natural course of events, this level of warmth might be reached about once in half a million years, perhaps as a consequence of an unusual combination of the astronomic factors that seem to be responsible for the timing of the major glacial–interglacial climatic changes[55]. Furthermore, because the present interglacial has apparently passed its natural peak of warmth—this was probably reached about 9,400 yr ago in the Southern Hemisphere[55]—deglaciation of West Antarctica would not occur in the foreseeable future without Man's injection of massive amounts of industrial CO_2 into the atmosphere.

If the recent growth rate of fossil fuel consumption continues, atmospheric CO_2 content is expected to double in about 50 yr. Present models of the climatic effects of this doubling compute a rise in temperature that could cause rapid deglaciation of West Antarctica, leading to a 5 m rise in sea level. Although the models are known to be crude and over-simplified, so that the climatic changes that will actually occur will no doubt differ considerably from their estimates, there is, at present, no way of knowing whether the models err on the optimistic or pessimistic side.

If the CO_2 greenhouse effect is magnified in high latitudes, as now seems likely, deglaciation of West Antarctica would probably be the first disastrous result of continued fossil fuel consumption. A disquieting thought is that if the present highly simplified climatic models are even approximately correct, this deglaciation may be part of the price that must be paid in order to buy enough time for industrial civilisation to make the changeover from fossil fuels to other sources of energy. If so, major dislocations in coastal cities, and submergence of low-lying areas such as much of Florida and the Netherlands, lies ahead. More sophisticated climatic modelling may show that the outlook is less alarming than this, but on the other hand, it may show that the situation is even more threatening. The urgent need for this sophisticated modelling is evident.

One of the warning signs that a dangerous warming trend is under way in Antarctica will be the breakup of ice shelves on both coasts of the Antarctic Peninsula, starting with the northernmost and extending gradually southward. These ice shelves should be regularly monitored by LANDSAT imagery.

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Can a myosin molecule bind to two actin filaments?

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It is suggested that in striated muscles the two heads of one myosin molecule are able to interact with different actin filaments. This would provide a simple explanation for the appearance and arrangement of cross-bridges in insect flight muscle in rigor.

The myosin molecule has two globular heads attached at one end of a fibrous tail[1]. During muscle contraction the heads are thought to bind to actin filaments and produce tension by tilting[2], but the way in which this is shared by the two heads is not known. It is widely supposed that the two heads of one myosin molecule interact with neighbouring subunits in the

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