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Rock Weathering, Soil Development and Colonization under a Changing Climate [and Discussion]

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Rock weathering, soil development and colonization under a changing climate

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SUMMARY

Antarctic continental soils are arid, saline and lacking in organic matter, whereas maritime soils, in a wetter environment, range from structureless lithosols to frozen peat. Two important factors in the development and diversity of their associated terrestrial communities are water availability and the period of exposure since deglaciation. The retreat of ice sheets offers new sites for colonization by microbes, plants and animals.

The interactions between snow lie, freeze–thaw cycles, wet–dry cycles and the length of the summer are considered as critical in determining the extent and rate of localized changes in weathering and pedogenesis. The implications of higher temperatures and differing precipitation régimes are considered in relation to weathering, soil development and the establishment and development of terrestrial communities.

It is concluded that, in the context of decades, most changes will be slow and localized. They are unlikely to be of regional significance, unlike some of those in the Arctic. They will, however, provide a good model of how present soils and communities developed at the end of the last glacial maximum.

1. INTRODUCTION

According to many researchers increasing concentrations of atmospheric greenhouse gases could cause global mean annual temperatures to rise by 2° to 5°C over the next 50–100 years. With respect to the polar regions, Ramanathan (1988) suggests that this temperature increase could be amplified by factors of 1.5–3, thereby producing a warming of 3° to 15°C. The threefold increase will take place primarily during winter and around the margins of the sea ice within the 50° to 70° latitudinal range. The 1.5 factor increase would be a spring-time effect but restricted primarily to the high latitude continents. Due to the melting of ice and snow cover the exposed underlying ocean or land, being much darker, will absorb more solar radiation and thus enhance the initial warming (Dickinson 1986). This 'ice-albedo' feedback could amplify global warming by 10–20% (Ramanathan 1988). In addition, it is possible that near the sea-ice margins the warming could be larger than the global warming by factors ranging from 2 to 4 (Ramanathan 1988). However, Bretherton *et al.* (1990) find that if a dynamic ocean model is utilized then establishment of a large, positive ice-albedo feedback is precluded and the warming may be minimised rather than accentuated. Nevertheless, whatever the magnitude of the actual increase, it will clearly have a significant impact on both polar regions.

The implications for the Arctic terrestrial ecosystems are already under consideration in several countries and will not be examined in any detail here. However there are several valuable indicators from the Arctic which can be used in the development of predictions for the Antarctic. The emphasis in this paper will be more on the maritime Antarctic than on continental Antarctica simply because significant local ice sheet recession has already been detected there.

2. ROCK WEATHERING

One result of the increased temperatures is expected to be a diminution of the polar ice cover, although in the short term the effects will be more immediate and greater for small glaciers and marginal ice sheets. In fact, on the continent there might be glacier growth as a result of increased snowfall. Major ice loss will be more apparent in the smaller and thinner glacial ice of the maritime Antarctic where it may be aided by an increased percentage of precipitation falling as rain rather than snow. This loss of ice will not only affect the terminal regions of the glaciers and ice caps but will also result in a greater exposure of rock on nunataks and valley walls as the glaciers thin. Thus, as the ice retreats so more land, at all altitudes, will be exposed to subaerial processes. As there will be an ever increasing aerial source of rock material and weathering processes are likely to be more active (see below) so the glaciers will be provided with a greater supraglacial debris load. Consequently, as the ice retreats the former glacier-covered area will be mantled by an unconsolidated till deposit of multi-sized, poly-litho-

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logic material subject to weathering at a faster rate than the bedrock (Hall 1986). In turn, this suggests that pedogenic and colonization processes will be be operative sooner and more rapidly than if that till mantle had not been deposited.

The loss of ice cover, particularly if it is rapid, can cause the formation of microfractures in the bedrock as a result of the removal of the constraining overburden. Failure planes, due to tensile forces, result in the splitting of the bedrock parallel to the slope surface (Kawamoto & Fujita 1968 in Yatsu 1988). This fracture system greatly facilitates and enhances weathering by providing a ready means of ingress for the water required for the operation of most mechanical and chemical weathering processes. In addition, Crook & Gillespie (1986) suggest that both granitic and sedimentary rocks can ultimately disintegrate completely as a result of stress relief alone. The fracturing due to stress relief is particularly active on steep slopes (see Yatsu 1988, Figs. 2.2.23 & 2.2.24) and valleys and nunataks undergoing glacial retreat will be particularly vulnerable to weathering, further increasing the debris supply to the retreating glaciers.

Although weathering rates are strongly controlled by climate, micro- and nano-climatic data are not yet adequate to allow comparisons, either temporally or spatially, within the Antarctic. In addition, the results of most laboratory weathering experiments are of doubtful value as indicators of actual weathering rates as the experimental régimes rarely replicate natural conditions (Thorn 1988). Considerations of scale cannot be ignored in any attempt to link ecological and atmospheric models (O'Neil 1988), but the problems of scale at the terrestrial–atmospheric interface are both great and complex (Dickinson 1988). Weathering processes, at both landscape and niche levels, operate at temporal and spatial scales orders of magnitude lower than those proposed for climate change. Although these problems of determining the scale of study and elucidating weathering rates are very real, neither can enter signficantly into the present discussion since we know so little about Antarctic weathering rates and processes (Hall 1992) that we are not yet in a position to deal with these factors in detail. Thus, in this discussion we can only consider the changes to weathering as a result of a warming climate in broad, somewhat speculative, terms.

A further ramification of increased temperatures is that they will cause thawing of permafrost. Permafrost, which is ubiquitous throughout the ice-free areas of Antarctica (Campbell & Claridge 1987), is ground that remains at or below 0°C for at least two years. Even though the permafrost may not entirely disappear in all areas, although this is a possibility in parts of the maritime Antarctic, nevertheless the zone above the permafrost that thaws each year (the 'active layer') will increase in depth. This is extremely important for a number of reasons. First, weathering, soil development and colonization can only take place in the active layer (Carter 1990). Second, at the present time temperatures are such that there is no active layer (Campbell & Claridge 1987), or it is extremely thin, on most of the continent. Thus, with warming, even the extremely cold areas are likely, with time, to experience the development and deepening of an active layer. Third, the unfrozen moisture present in an active layer facilitates the operation of cryogenic processes such as frost sorting, frost heave and gelifluction all of which interact with weathering, soil development and colonization.

Warming will thus progressively increase the zone available for weathering, pedogenesis and colonization in all spatial dimensions. Clearly, this will not be equal everywhere in the Antarctic, there being a dimensional increase along a transect from the continent interior through the Antarctic Peninsula to the maritime Antarctic (figure 1). Along this transect ice

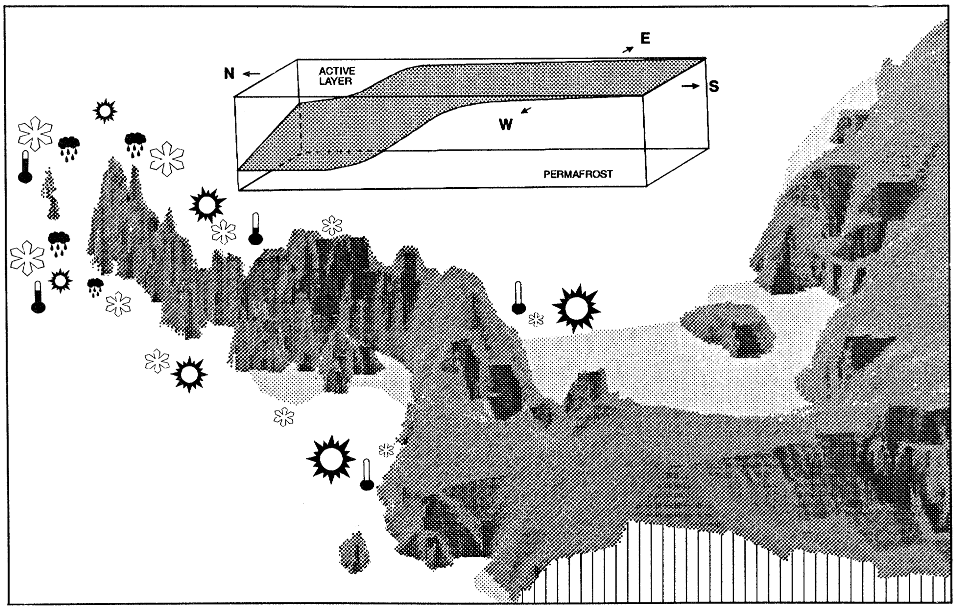

Figure 1. Simplified map to show the spatial variability of permafrost and climatic parameters from the maritime to continental Antarctic.

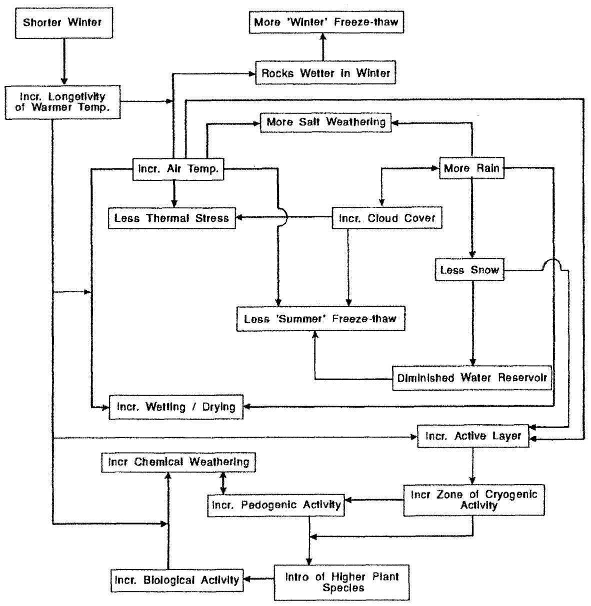

Figure 2. A flow diagram to show some of the effects of climatic warming for the maritime Antarctic environment.

thinning and retreat will be, in the short time frame, least on the continent and greatest at the northern extremity of the maritime zone. Equally, the deepening of the active layer will be most rapid in the maritime zone where present summer temperatures have already melted the permafrost to a depth of over 1 m in places. However, once established on the continent the existence of an annual active layer could have a marked effect on cryogenic and pedogenic processes. A further result of climatic warming would be to increase the temporal dimension with respect to weathering, pedogenesis and colonization. Along the same spatial transect described above there would be a diminution of the longevity and severity of cold conditions and a consequent increase, again greatest in the maritime zone, in the annual period available for active weathering.

3. WEATHERING AND SOIL DEVELOPMENT

Weathering is the precursor to soil development to the extent that many workers recognize a two stage situation rather than a continuum. For instance, Matsui (1969) identifies weathering as the transformation of bedrock to detrital sediment whereas pedogenesis is the change from sediment to soil (the stages of 'geochemical weathering' and 'pedogenic transformation' according to Millot (1982)). However, in spite of this bipartite division the factors that control both weathering and pedogenesis are essentially the same, namely climate, parent rock, topography, vegetation, hydrological conditions and time (Yatsu 1988). Here it will be chiefly the effects of climate that are considered. Both topography and vegetation (due to its spatial and temporal limitation within the Antarctic) are highly site specific. Although hydrological conditions are considered with respect to rock moisture content, the weathering and pedogenic associations with drainage are ignored as these are again constrained by local conditions. Parent rock is important at two levels, those of physical properties and of rock chemistry. Both are briefly considered here but in broad terms rather than in specific detail. Finally, time is of particular significance with respect to weathering for, given adequate time, even the chemical effect of the parent rock can be nullified (Chesworth 1973). However, it is the immediate to short time span that is discussed here and so the longer-term effets of time on various attributes of both weathering and pedogenesis are ignored.

Two broad climatic scenarios are considered, both involving a warmer climate but differing in terms of precipitation régimes. The first, which is applicable to the continental environment, involves a higher than present snowfall whereas the second, which is relevant to the maritime Antarctic, entails increased precipitation in the form of rain. These changes in precipitation, in conjunction with higher temperatures, will have varying effects upon the present temporal and spatial disposition of weathering processes. In some instances certain weathering processes will be initiated or enhanced whereas in other instances current processes will be inhibited and succeeded by a new weathering suite. The nature of weathering will change, producing different weathering products which, in turn, will have both direct and indirect effects upon pedogenesis and colonization.

Considering first the maritime end of the spectrum (figure 2). The change here is primarily controlled by a greater incidence of precipitation in the form of rain. If total precipitation remains unchanged the corollary of more rain is less snow. Combined this means that whilst there will be a more frequent and comprehen-

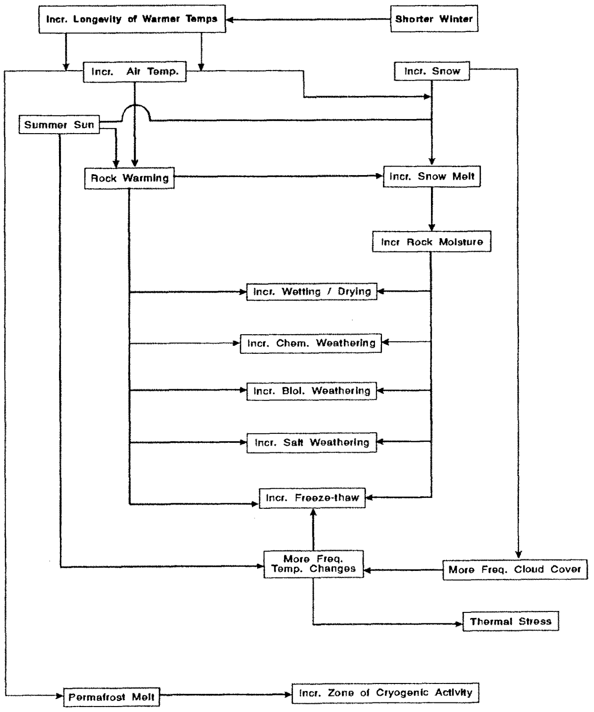

Figure 3. A flow diagram to show some of the effects of climatic warming for the continental Antarctic environment.

sive wetting of the rock, there will be a more limited reservoir of water (i.e. snow) to be released to the rock during times of high temperature. At present, during the summer, cold phases frequently follow warm periods and so freeze-thaw can take place at those locations wetted by snowmelt. With both warming and a greater incidence of rain there is likely to be less freeze-thaw during the main spring to autumn period. Only if rain precedes the freeze at the end of autumn will frost action take place during this 'summer' period. Thermal stress fatigue, although not apparently a major agent in the maritime Antarctic, may be further inhibited by the increased cloud cover.

Conversely, with global warming effectively extending the length of the summer and the rain facilitating extensive wetting of rock, so the weathering process of wetting and drying becomes temporally and spatially more active (figure 2). Salt weathering is also enhanced, with salts being introduced or mobilized during the wetting phase and crystallization occurring during drying. Wetting–drying cycles and salt weathering both operate in the outer shell of the rock, producing small sized debris which is difficult to partition between processes. The more frequent presence of rock moisture combined with higher temperatures will also promote chemical weathering. The combination of more active weathering processes together with their synergistic interaction will result in increased overall weathering rates.

If the higher temperatures are combined with decreased snowfall this will produce a rapid deepening of the active layer (figure 2). As the active layer deepens and more moisture is made available from rainfall so there will be an increase in pedogenic activity. In turn, these changes may facilitate the establishment of vegetation, including, in the more favourable areas, higher species of plants. The combination of greater pedogenic activity, increased moisture availability, higher temperatures and a greater abundance of plant life will generate increased chemical and biological weathering. Although this will not affect bedrock, except perhaps at the base of outcrops, this enhanced weathering will mean more rapid breakdown of glacial debris, scree and other redeposited, non-consolidated materials.

At the continental scale, the rise in temperature combined with increased snowfall effectively moves the present continental-margin conditions inland. The higher incidence of cloud cover associated with an increased frequency of snowfall will produce greater temperature variability at the rock surface (figure 3). The main source of rock moisture is the melting of snow in contact with rock heated by the sun. Now, with increased snowfall and higher overall temperatures there should be a greater amount of melt and so higher rock moisture levels. Thus, freeze-thaw weathering is likely to become a more active and effective process (figure 3). More frequent thermal changes resulting from clouds obscuring the sun may also increase the role of thermal stress fatigue. However, it is the relatively greater presence of rock moisture that is the key factor, for its absence at the present time is the main constraint upon weathering. With more rock moisture so, relative to the present, there will be a greater incidence of wetting and drying and of salt weathering (figure 3). Equally, the potential for chemical and biological weathering will also increase as a result of these changes in climatic conditions.

Weathering due to chemical, biological, wetting–drying and salt crystallization processes are all largely superficial. In fact, it is expected that all but salt weathering will show only minor and localized increases and, as such, they will have little significant influence on the general scale of weathering. However, in terms of their singular or combined effect upon debris production at any one site the resulting material will be both small in size and overall volume. Freeze–thaw may also be primarily a superficial process but if adequate moisture is provided and the rock is highly porous, particularly if in the form of microfractures, then the effects may go deeper and the resulting debris would then be larger. The large temperature differentials that can occur in Antarctica may allow thermal stress fatigue to produce both large and small debris in some rock types. The larger particles will be generated when the temperature differentials are sufficient to cause stress at depth within the rock or when the rate of temperature change facilitates thermal shock and the consequent catastrophic failure of the rock. Overall, the most important factor is that, in combination, there will be an increase in both weathering processes and weathering rates on continental outcrops of rock.

4. SOILS AND TERRESTRIAL ECOSYSTEMS

In the high polar regions the development of soil is a very lengthy process (figure 4), constrained both by temperature and by the availability of liquid water. Cold soils may be very saline and largely ahumic because of a lack of biological activity (Campbell & Claridge 1987). In lower polar latitudes a much wider range of soils has developed, linked primarily to organism diversity and organic decomposition processes.

Some authors have concluded that the increased temperatures at high latitudes will have different effects at each pole. For the Arctic the climate may get warmer and wetter resulting in the reduction of permafrost and glacial ice as well as the progressive loss of sea ice. In the continental Antarctic increased snowfall would increase continental ice cover, increase iceberg production and intensify the Antarctic Convergence (Houghton *et al.* 1990) although glaciers in the maritime Antarctic would continue to retreat.

In a recent volume which examined the possible effects of greenhouse warming on soils (Scharpenseel *et al.* 1990), there were some useful general reviews of how processes in general might be affected. Many of them are relevant to Arctic soils with their comparatively well developed structure and considerable area. In their examination of boreal and subarctic regions Goryachkin & Targulian (1990) summarized the possible effects of wet warming and dry warming on 16 soil properties in nine soil units. Their general conclusion is that there is no general pattern: the

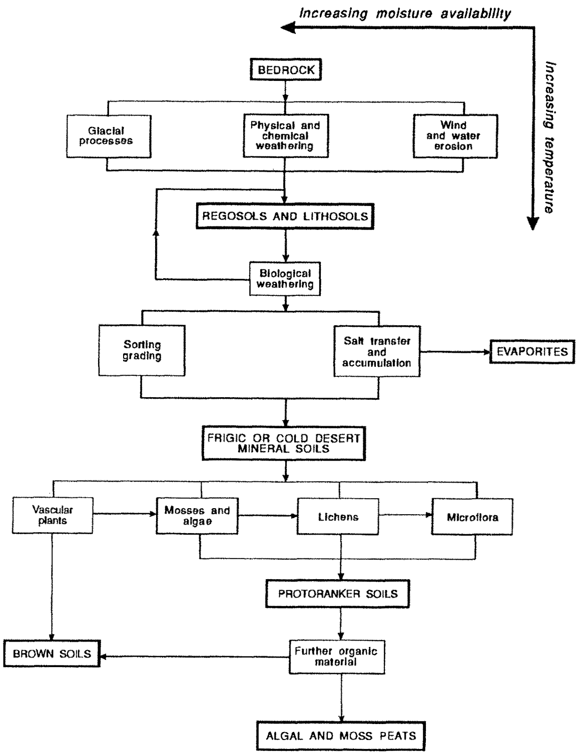

Figure 4. Diagrammatic representation of principal stages in the development of polar soils (after Stonehouse 1989).

different soil properties each have their own characteristic response time and this causes soil properties to change differently in both rate and frequency. They highlight the principal problem of moving to a more quantitative model as a lack of understanding of the links between spatial and temporal change in soil evolution, and a lack of data on time constants for soil processes in each soil type. On present data they conclude that most boreal and subarctic soil will change little in less than 100 years. Peats (Histosols), coarse mineral (Podzols) and calcareous soils (Rendzinas), wet soils (Gleysols, Histosols) and primitive soils (Lithosols, Regosols, Andosols) are especially resistant to change even over a period of 1000 years. The soils expected to change most are those formed from medium textured substrate with developed horizons and active soil processes, none of which occur at present in the Antarctic.

Dregne (1990) comments briefly on the possible effects of climate warming on polar soils in a review of effects on arid soils as a whole. He suggests that warmer temperatures would increase plant growth, soil organic matter and the depth of the active layer in the Arctic. In the Antarctic he predicts a very small increase in soil organic matter. There are, however, likely to be much more rapid changes close to the soil surface with important feedback effects on both vegetation and soils. As with the maritime Antarctic, the overall warming will lead to melting of permafrost and hence to increased cryogenic activity. On the continent the melting will be slow. This is partly due to the severely cold conditions that prevail such that a slight rise in temperature would have a limited effect on the permafrost and it would be some time before this became apparent. A contributing factor to the delaying of permafrost degradation would be the protective effect of an increased snow cover. However, as, with time, there will be a deepening of the active layer so the moisture provided by the melting snow would be extremely important for cryogenic and pedogenic activity. Further, Balke *et al.* (1991) have shown that chemical weathering currently takes place in the active zone for about 10 weeks each year in some ice-free areas of the Antarctic continent. With longer summers and additional warming so the potential for chemical weathering and pedogenesis would increase.

Even though most Antarctic soils are largely ahumic there are maritime peat soils and even some small areas under the grass *Deschampsia antarctica* where a simple Brown soil develops. In all these areas and in the ornithogenic soils associated with penguin rookeries nutrient cycling takes place by microbial action. The species involved are not psychrophilic so that increased temperatures could be expected to produce increased breakdown of organic matter at sites where water was not limiting (Wynn-Williams 1990*a*). Thus, in the maritime Antarctic which is likely to have the greatest increases in both temperature and precipitation, there will be a decrease in peat accumulation and an increase in nutrient availability and pedogenic development.

5. COLONIZATION

In a review of the possible effects of climate change on high latitude regions Roots (1989) listed critical questions where knowledge is lacking. Especially pertinent to soils and the terrestrial ecosystems at both poles are the following:

1. What is the relation between changes in high latitude albedo (increase or decrease of net areas of snow and ice) and surface temperature?
2. What is the relationship between average and extreme temperatures, available photosynthetic energy and nutrient supply in limiting biological production?
3. What are the combinations of topography, nutrient supply and microclimate that control biological productivity?
4. What is the relative and absolute role that areas of high productivity play and are these especially sensitive to change?
5. What are the rates and ranges of dispersal, colonization or die-off among key species in polar communities under climate-driven changed environmental conditions?
6. What changes in biological communities or biological succession will signal adaptation to, or disruption by, climate change?

It is not possible to examine the limited evidence for all of these questions in this paper. Attention will be focused on two specific areas: micro-environmental variables, and species diversity and survival.

The change in thermal and moisture status of rock and soil is very important with respect to the distribu-

Figure 5. Flora of geothermally heated ground on Deception Island contains many species not found elsewhere in the Antarctic. (Photograph: R. I. Lewis Smith.)

tion of plant species and the overall thermal balance of the ecosystem (Rejmánek 1971). The Antarctic flora shows a clear gradient of climatic tolerance with a decreasing proportion of liverworts and mosses and an increasing proportion of lichens (especially crustose species) as available free water becomes more limited. In the continental Antarctic aspect, topography, wind protection and meltwater drainage patterns are all crucial features defining acceptable niches for all organisms. It is important to remember that under such difficult circumstances organisms may well prefer to colonize the surface or the internal fabric of rocks rather than the surrounding soil, and that as yet we have almost no understanding of the temporal and spatial availability of specific niches to would-be colonisers (Walton 1990).

The evidence that higher temperatures will allow an increased diversity of flora is already manifest in data from geothermal areas. In the Arctic the hot springs in Greenland support species that are either unrecorded elsewhere in Greenland or reach their northern limit in the heated ground (Halliday *et al.* 1974). In the Antarctic both Deception Island and the South Sandwich Islands have specific cryptogamic communities characteristic of heated ground (Longton & Holdgate 1979), with that on the latter islands being considerably richer and more luxuriant than elsewhere (figure 5). Of the plant species recorded from the South Sandwich Islands six of the 13 algae are restricted to fumaroles, as are one of 27 lichens, eight of 30 mosses and seven of 12 hepatics. Many of the species found on unheated ground were also found growing much more luxuriantly in the fumarole communities.

Collins (1969) recorded the presence of a *Funaria* cf. *hygrometrica*, previously unknown from the Antarctic, in a new fumarole on Deception Island. A more detailed survey of heated ground on the island (Lewis Smith 1984) showed that *Leptobryum* cf. *pyriforme*, *Marchantia berteroana* and *Philonotis gourdonii* are all found only in this habitat within the Antarctic although the first two species are widespread in more temperate regions.

There are only two native phanerogams in the Antarctic: *Deschampsia antarctica* and *Colobanthus quitensis*. Although the species flower in most sites every summer the production of ripe seed occurred in only three of the nine seasons assessed (Edwards 1974). Experiments with cloches demonstrated that low temperatures limiting seed development were the cause of this. Climate warming should result in the spread of both these species.

There have also been various attempts to test the limits of survival of species introduced to the Antarctic. In the most extensive trials phanerogamic species from the Falkland Islands (Edwards & Greene 1973) and South Georgia (Edwards 1979) were transplanted to Factory Cove, Signy Island between 1967 and 1973. Out of 23 Falkland species 11 survived for over two and a half years on Signy but only two produced new flowers. The South Georgian species did better. Of 23 species 14 survived for at least one year and eight species produced new flowers some, such as *Phleum alpinum*, every year for 4 years. Seedlings of eight species became naturally established during the summer months but mortality of the seedlings was high during the winter. In general the species most capable of survival were the graminoids and some of the persistent alien species. On the evidence available so far the most likely new colonizer in a warming environment is the almost cosmopolitan alien grass *Poa annua*.

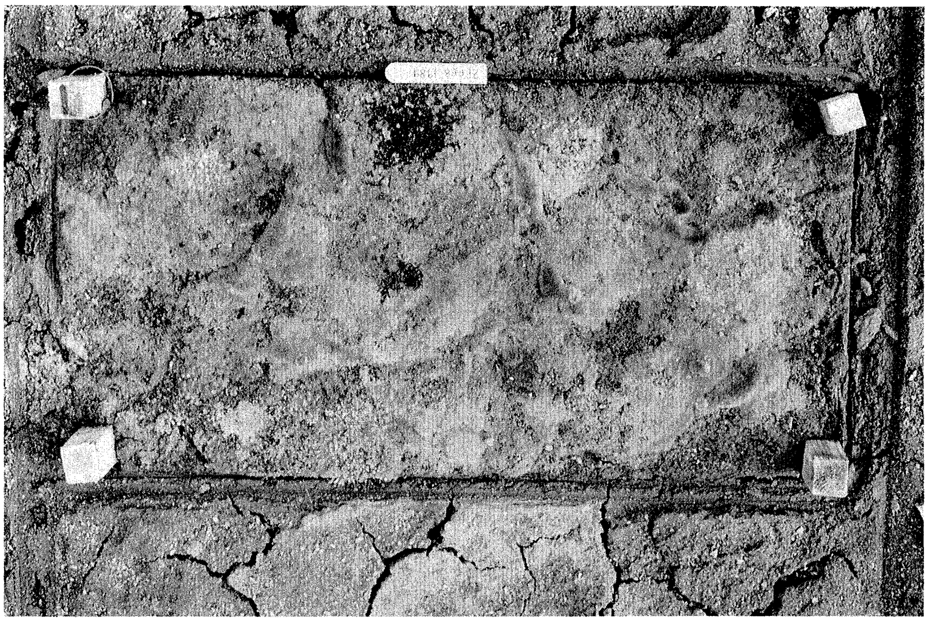

Figure 6. Manipulation of the microclimate with plastic cloches illustrates the potential for colonisation of bare ground by species already present in the soil propagule bank. The 100% cover by mosses and algae shown here has developed under the cloche in three years on the bare sorted centre of a polygon at Signy Island. (Photograph: R. I. Lewis Smith.)

These observations suggest that, if present environmental conditions ameliorate, there will be an increase both in species diversity and in annual growth. The diversity might arise either from an increased opportunity for propagules already present in a soil bank to germinate and grow, or by increasing the probability of incoming propagules finding an acceptable niche in which to establish (Walton 1990). Two approaches have begun to test this.

Lewis Smith (1987) has proved the existence of a substantial diaspore bank in recently deglaciated soils on Signy Island from which a wide range of species can be cultured under laboratory conditions. The next stage was to manipulate the environment to see if these diaspores would establish naturally. Plastic cloches were placed on the unvegetated centres of sorted polygons to increase temperature and humidity, decrease wind exposure and lengthen the growing season (Wynn-Williams 1990*b*). Dramatic changes were evident when the cloches were compared after three years with nearby uncovered controls (table 1). Almost three quarters of the soil surface was now covered with algae under the cloche but only 5% on the control site. The cloches provided a 3.2°C increase in mean summer temperature as well as a continuously humid environment. There are other effects which may also have contributed significantly to the change. The cloches lengthen the growing season by excluding snow, by increasing thermal inertia they reduce the frequency of freeze–thaw cycles and they screen out a high proportion of UV-B. A new experiment has now begun using multiple cloches of various designs to test the interactive effects of each of these environmental variables (D. D. Wynn-Williams, personal communication). Thus the potential is already present at this maritime site to develop more extensive vegetation cover under a warmer and wetter régime. Similar experiments with cloches are now being undertaken at a range of other Antarctic sites.

Table 1. *The response of Antarctic soil algae after three years of improved environmental conditions under a plastic cloche (from Wynn-Williams 1990b)*

	control	cloche	% change
temperature/°C[a]	4.4 ± 1.2	7.6 ± 1.7	+73
area colonized (%)	4.8 ± 1.5	7.39 ± 8.0	+1440
total length of cells[b] (μm 10^{-3} mm^{-2})	3.9 ± 2.0	17.9 ± 7.4	+358
cell length/μm	25.3 ± 1.7	78.0 ± 45.2	+208
cell breadth/μm	10.2 ± 1.6	7.1 ± 0.9	−30
cell volume/μm^3	1641 ± 479	4719 ± 3744	+188

[a] Integrated surface temperature January–March 1988.
[b] All cellular data obtained by television image analysis.

Two ecological questions remain to be asked. First, how will the existing communities change under a warmer and possibly wetter environment? It is clear from the cloche experiments that changing the environment changes the competitive interactions between species in communities since the pioneer communities under the cloches differ from those found at present on the island. As yet there are no data from cloche manipulations of established communities.

Second, with an increasing snow free area available for colonization will there be a major increase in species diversity due to the establishment of pioneer species from outside the Antarctic? At present little is known about the potential offered by the air flora for new colonising species. The palynological record in peat banks show clear evidence of the arrival of exotic tree pollens in the subantarctic (Barrow & Smith 1983) and the maritime Antarctic (Kappen & Straka 1989) but there is almost no data on the diversity, likely origin and potential viability of any other aerobiological particles. The new SCAR BIOTAS (Biological Investigation of Terrestrial Antarctic Systems) programme is therefore attempting to address propagule input to both the islands and the continent by a coordinated international effort (Wynn-williams 1992).

The most notable attempts to bring together existing terrestrial data to characterize climatic change have almost all been based on soils in the Dry Valleys or on the ecosystems on Signy Island, South Orkney Islands. Campbell & Claridge (1987) have described climatic changes in Victoria Land over the past 5 million years based on their characterization of patterns and rates of soil development. The key environmental feature of this is the continued aridity of the area, which has effectively limited development of both physical structure and chemical content.

As long ago as the early 1970s Collins (1976) recognized that short-term fluctuations in climate could be identified from vegetation patterns on Signy Island: 'trim lines' alongside glaciers, re-exposure of subglacial peat banks, etc. Lewis Smith (1990) took this approach much further and by indicating the possible changes in ice extent over the past 7000 years has shown how this area at least responded to warmer temperatures in the past.

Future change in the mass of the Antarctic ice sheet will be slow in coming; either from increased precipitation or increased melting. What does seem clear is that at the continental margins and on the offshore islands change is already happening (Fenton 1982) and will continue to gather pace, illustrating the patterns which almost certainly provided the basis of change at the end of the last glacial maximum in temperate regions. In the timescale of 100 years it seems certain that any changes in weathering rates, soil genesis, colonization and community change will all be slow, very localized and unlikely to have any important regional impact or feedback.

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Discussion

D. D. Wynn-Williams (*British Antarctic Survey, Cambridge, U.K.*). Professor Hall mentioned that a warmer maritime Antarctic climate would result in more precipitation. During rock weathering, moisture would penetrate into the fabric of the rock and disrupt it by ice crystal expansion during freeze–thaw cycles. Microbes would penetrate the rock in the water film. At Signy Island, I have observed that most soil and rock microbial colonizers, both phototrophic algae and cyanobacteria, and heterotrophic bacteria, have substantial mucilagenous sheaths or capsules. These expand and contract greatly during wetting and drying and may therefore disrupt the rock structure even further by hydrostatic effects. Does he have any direct evidence of this?

K. J. Hall. Although I have no direct evidence from the maritime Antarctic, work undertaken in Alaska (Hall & Otte 1990) clearly showed that the expansion and contraction of the mucilagenous sheaths of endolithic algae caused extensive weathering of granitic rocks. The expansion was as a result of water absorption during times of precipitation while contraction took place during heating of the rock by solar radiation. Thus, with increased precipitation, particularly in the form of rain, so it could well be expected that this form of biological weathering would become more prevalent in the Antarctic.

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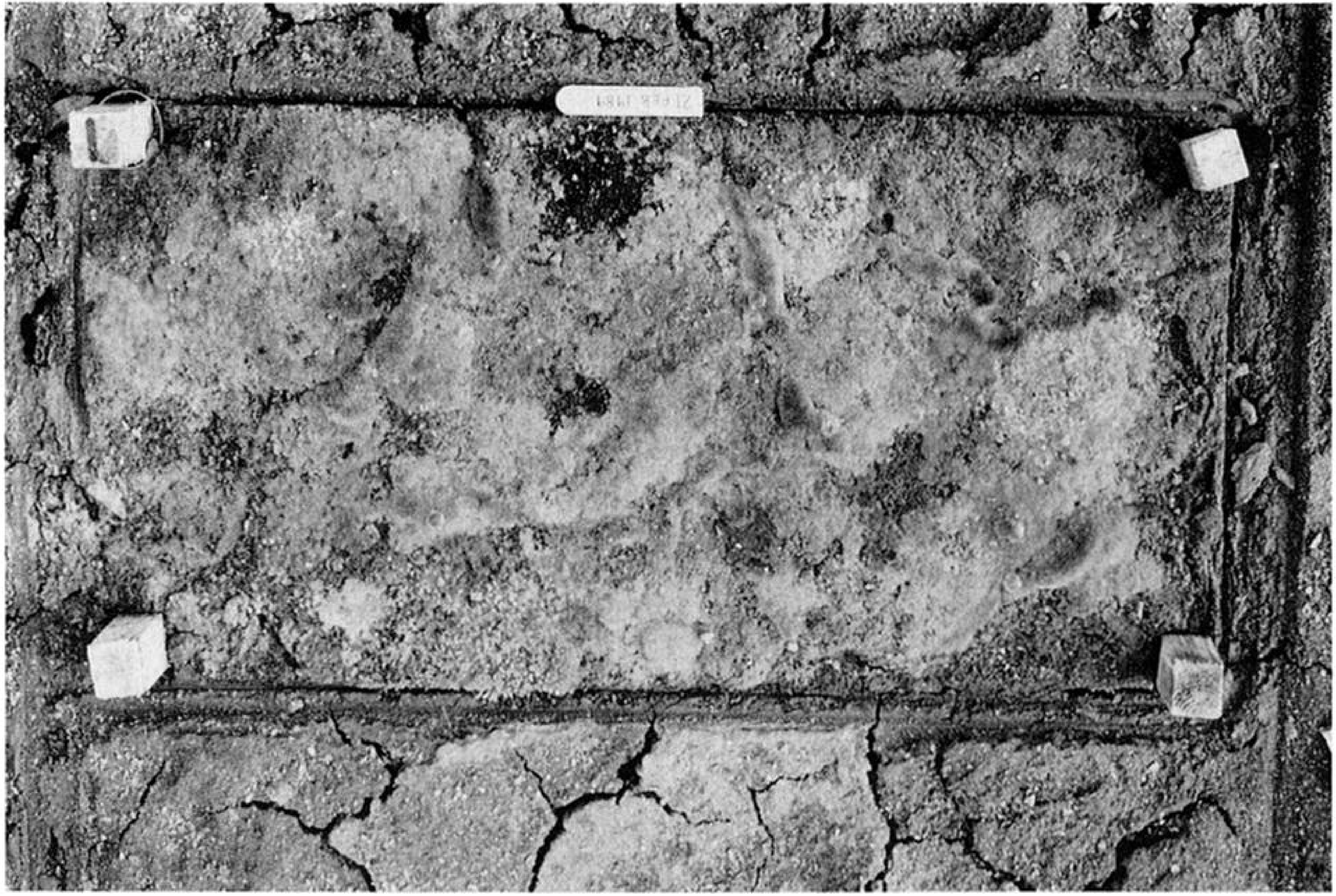
T. Callaghan (*Institute of Terrestrial Ecology, Merlewood Research Station, Cumbria, U.K.*). The measurement of Q_{10} of soils (the rate at which CO_2 is evolved in response to temperature increases) increased in organic soils in a transect from the sub-arctic to the High Arctic. In a lithosol from a High Arctic semi-desert, the Q_{10} was extremely high and could not be accounted for by microbial activity alone. This would suggest a significant evolution of CO_2 due to purely chemical processes.

D. J. Drewry (*British Antarctic Survey, Cambridge, U.K.*). In relation to weathering are there any data or experimental results which can be used to give the sensitivity of weathering processes to climate change: for instance mass loss per unit time per degree C.

K. J. Hall. Unfortunately the relationship of weathering to climate is so complex that it is impossible to provide any simple correlation regarding it, such as mass loss per unit time per degree C, particularly as some processes accelerate as others decrease. Further, at the moment our data base regarding process types and process rates is so small it would be impossible to make any judgements.

W. C. Block (*British Antarctic Survey, Cambridge, U.K.*). We may be slightly misled if we consider only plant or vegetation development as being affected by climate change in Antarctica. These communities have few invertebrate species and a simple structure where food chains are short and competition often very much reduced. Such simple communities may well be more sensitive to environmental changes and their responses faster than plants such as mosses and lichens. Secondly, there are likely to be more subtle changes in, for example, invertebrate physiology than the possible gross, large-scale changes seen in plants with climatic change. An example of this are the results of a long-term study of body water content in a typical Antarctic insect (the collembolan *Cryptopygus Antarcticus*). These data show a marked and significant upward trend in water content with increased water availability in their habitats over several years. This suggests that such species may have been living with body water levels below the optimum physiological level in such arid habitats. Such organisms may be more sensitive indicators of environmental change than has been thought hitherto.

gure 5. Flora of geothermally heated ground on Deception Island contains many species not found elsewhere in the Antarctic. (Photograph: R. I. Lewis Smith.)



igure 6. Manipulation of the microclimate with plastic cloches illustrates the potential for colonisation of bare round by species already present in the soil propagule bank. The 100% cover by mosses and algae shown here has eveloped under the cloche in three years on the bare sorted centre of a polygon at Signy Island. (Photograph: R. I. ewis Smith.)