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RECENT RAPID CLIMATE CHANGES IN ANTARCTIC AND THEIR INFLUENCE ON LOW DIVERSITY ECOSYSTEMS

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ABSTRACT: The geographic position, astronomic factors (e.g. the Earth's maximum distance from the Sun during winter), ice cover and altitude are the main factors affecting the climate of the Antarctic, which is the coldest place on Earth. Parts of Antarctica are facing the most rapid rates of anthropogenic climate change currently seen on the planet. Climate changes are occurring throughout Antarctica, affecting three major groups of environmental variables of considerable biological significance: temperature, water, UV-B radiation.

Low diversity ecosystems are expected to be more vulnerable to global changes than high diversity ecosystems.

KEY WORDS: Antarctica, climate change, nutrients, ozone hole, temperature, UV-radiation, water relations, human impact.

ANTARCTIC CONDITIONS AND THEIR INFLUENCE ON BIODIVERSITY

The isolation of the Antarctic continent, following the break-up of Gondwana, and the subsequent establishment of the **A**ntarctic **C**ircumpolar **C**urrent (ACC) have meant that the evolution of both marine and terrestrial biotas has taken place relatively undiluted by biotic exchange. The climatically dramatic Mesozoic caused major shifts in the composition of both marine and terrestrial biotas (Chown and Convey 2007). The present physical isolation of Antarctica allowed circum-Antarctic oceanic and atmospheric circulation patterns to develop, further isolating the continent from heat transfer from lower latitudes and accelerating the processes of continental cooling. These oceanic and atmospheric circulation patterns still restrict the transfer of biota into and out of Antarctica; it is clear that low levels of transfer have continued since their establishment (Clarke *et al.* 2005).

The vast contiguous mass of glacial ice covers the Antarctic continent and surrounding seas. It is the largest single solid object on the surface of the planet. Despite their relatively small surface areas (<50 000 km^2, only approximately 0,33% of total continent surface), ice-free areas in Antarctica (including nunataks, cliffs and areas exposed seasonally through snow melt or ablation, screes and rubble slopes, valley bottoms and coastal plains) represent the last pristine and the most extreme environments in the world (Fox and Cooper 1998). Moreover, the geological and glaciological histories of these ice-free areas differ substantially, which is not surprising, given the size of the continent. Thus, both local and regional environmental variation determines the spatial variation of current diversity across the continent (Peck *et al*. 2006). The typical pattern seen across the maritime and continental Antarctic zones is of ice-free areas that are small and isolated from other such habitat islands by even hundreds of km. At the largest scale, the continent of Antarctica is isolated from South America by approaching 1000 km, and by 4–5000 km from Australia and South Africa. These areas provide natural models of change that are influenced exclusively by climate change and/or other natural processes (Convey 2005).

The most distinctive feature of the polar region is the large seasonal variation in incoming solar radiation – from very little in winter to 24 hours of continuous sunlight in summer. The geographical location of Antarctica and its distance from the moderating influence of the ocean (especially when the Southern Ocean is covered with ice) determine very low temperatures over most of the continent. In summer the Antarctic receives even more solar radiation than the tropics, but the high albedo of snow and ice, aided by relatively cloud–free atmosphere that contains very little water vapour, ensures a net loss of radiation. The annual cycle of surface air temperature is characterized by a broad summer maximum (about –30^{o}C on the plateau, and –4^{o}C at coastal locations) and a minimum in winter (–70 ^{o}C on the plateau, and –25^{o}C at the coast). The total precipitation in Antarctica, averaged over the entire continent, is about 166 mm per year (Vaughan *et al*. 2001). The actual rates vary widely, from high values over the Antarctic Peninsula to very low values (as little as 50 mm per year) in the high interior. Thus, areas that receive less than 250 mm of precipitation per year are classified as a polar deserts. Almost all Antarctic precipitation falls as snow. The air in Antarctica is also very dry. The low temperatures result in the air in Antarctica being able to hold only very small amount of water vapour, even when close to saturation. Because of the lack of incoming solar radiation, the Antarctic stratosphere in winter is extremely cold. A strong temperature gradient develops between the continent and mid-latitudes, isolating a pool of very cold air above the Antarctic. Very strong winds develop along this gradient pool of cold air and its strong surrounding winds together from the polar vortex. A very characteristic feature of the Antarctic climate are katabatic winds. Intensive cooling over sloping ice surfaces produces a horizontal pressure gradient force with a downslope direction. The minimum velocity therefore coincides with the top of the inversion layer, and the strongest winds occur in the coastal escarpments – even a 40m s^{-1} (Bargagli 2005).

Most Antarctic soils are poorly developed, with low organic and nutrient content. The autochthonous resources of biogenic substance available for Antarctic communities are minimal (Engelen *et al.* 2008). Brown soils and protorankers, familiar from lower latitudes, are only found in association with communities of vascular plants and so are of very limited representation in the maritime Antarctic (Lewis Smith 1984). Extensive moss peat and histoslos deposits are also only present in the maritime Antarctic (Birkenmajer *et al.* 1985). Leptosols, regosols and podzols are typical soil formation of the coastal continental Antarctica (Blume and Bölter 1993). Among the spectrum of abiotic factors involved in the relatively simple Antarctic ecosystems, soils and their properties are an important element (Holdgate 1970). Antarctic soils are frequently exposed to climatic freeze–thaw events that lead to disturbance of substrata by cryoturbation (Hall and Walton 1992). Permafrost is widespread in the maritime and continental Antarctic. In combination with frequent cryoturbation, the result is that Antarctic soils are particularly unstable and mobile, factors affecting the ability of biological propagules to establish and the survival of biota and, hence, the development of ecosystems (Convey 2005, Wynn-Williams 1993).

INFLUENCE OF ANTARCTIC CLIMATE ON BIODIVERSITY

The Antarctic biota occurs mainly in the small ice-free locations located mainly in coastal areas of maritime Antarctic; outside this zone vegetation is primarily limited to a few rocky outcrops along the coast, the Dry Valleys and nunataks. The maritime Antarctic climate is markedly seasonal, with a strong see influence, especially during summer, that becomes reduced during winter through seasonal sea ice formation. Antarctic terrestrial ecosystems experience low thermal energy input, even relative to those of high northern latitudes (Danks 1999). Antarctic terrestrial biota are generally limited by the inexorably linked environmental factors of low summer temperature with frequent subzero temperature and of available liquid water with desiccating winds, intermittent water supply, of highly seasonal light regime, and more recently, elevated ultraviolet-B radiation level, with many seasonally related environmental stresses. The extreme thermal seasonality experienced across much of the Antarctic, which increases both with latitude and with distance from the coast and the moderating influence of the surrounding ocean, restricts biological activity. Even where the thermal environment is suitable for biological activity, further limits are imposed by desiccation (governed by interactions between precipitation, snow, ice or permafrost melt, ablation and wind) (Schlensog *et al.* 2004).

There are strong contrasts in the species diversity of terrestrial versus marine ecosystem in the Antarctic. Terrestrial biota is generally very poor in species in comparison with almost all other environments worldwide, with absence of many functional groups: missing completely or very poorly represented (Blok 1984). For instance, only two higher insects and two flowering plants are present in the maritime Antarctic. Antarctic terrestrial animal communities are dominated by invertebrates and some of them are recognized as the simplest on the planet (Freckman and Virginia 1997). The majority of invertebrates are thought to be microbivores or detritivores, and predation pressure is minimal (Hogg *et al.* 2006). For example, the lack of true herbivores is also unusual on a global scale (Convey and Lewis Smith 2006). Trophic structure of Antarctic terrestrial ecosystems is very simple. Only two vascular plants (Deschampsia antarctica and Colobanthus quitensis) are known from the entire Antarctic continent, both restricted to coastal regions of the Antarctic Peninsula and associated archipelagos. As a consequence of polar severe conditions, Antarctic tundra consists almost entirely of cryptogams with lichens, predominating in drier, more exposed sites (Olech 2004) and bryophytes, prominent in the more sheltered and humid habitats (Ochyra 2008). Outside the maritime zone the vegetation is primarily limited to a few rocky outcrops along the coast, the Dry Valleys and nunataks. Minimal information is available for most microbial groups, despite the recognition that microbial autotrophs are fundamental to polar terrestrial ecosystem processes (Vincent 1988), as they are worldwide. As well as being primary colonists and sometimes the only primary producers or biota present, fungi, algae and cyanobacteria are also important in stabilizing mineral soils, and in the development of suitable substrata for secondary colonists (Adams *et al.* 2006). Microbial communities are present across the Antarctic (Vincent 1988). As well as terrestrial habitats, they are also found in cryophilic habitats, such as in snow and cryoconite holes that develop in glacier surfaces (Grzesiak *et al*. 2009). Communities of the most extreme Antarctic environments appear to be at the first stages of colonisation or succession, and are limited purely by the extreme conditions rather than biotic interactions. Living at the limits of life, they are expected to be particularly sensitive indicators of changes in climate or consequential processes (Frenot *et al*. 2005).

ANTARCTIC CLIMATE CHANGES

In the context of climate change, three elements are fundamental to the biology of Antarctic terrestrial organisms: temperature, water and solar irradiance. Therefore, even a small shift in temperature, precipitation and liquid water availability may have an important biological impact.

Air temperature: The long temperature records from the Antarctic Peninsula and associated archipelagos have trends an order of magnitude greater than global mean warming (0.6 ± 0.2 °C (century)$^{-1)}$. Station records show that the Antarctic Peninsula has warmed at 3.7 ± 1.6 °C century)$^{-1}$, several times the rate of global warming and quite different to most of the records from the Antarctic continent. For example, there are reports of regional cooling in the Dry Valleys, which can be interpreted in the context of consequences for the ecosystems (Doran *et al.* 2002). This recent rapid regional warming on the Antarctic Peninsula has reportedly caused retreat of glaciers (Smith *et al*. 1999) and reduction of snow cover (Fox and Cooper 1998). Furthermore, where summer melting does not occur, increased precipitation appears to have caused some thickening of the ice sheet. Only the Antarctic Peninsula has shown an increase in the duration of the warm period over the past 20 years, at a rate of 0.5 ± 0.3 days year^{-1}, over a mean of 38.9 days melting per year (Mercer 1978). Vaughan (2006) also expressed this level of warming in terms of the increase in cumulative day degrees above 0 °C. A significant feature of the Antarctic Peninsula warming is that much stronger trends are seen in the winter months (11±9°C per century), with much lower, but still significant rates seen in summer (2.4±1,7°C per century) (King *et al.* 2003), effectively shortening the winter season. This, as well as earlier spring thaws and later autumn freezing, may extend the active season for terrestrial biota.

Water availability: Temperature is not the only biologically important environmental variable undergoing contemporary change. It is recognized that availability of liquid water plays even a more important role as a key environmental variable influencing distributions and activity of polar terrestrial organisms (Kennedy 1993). Precipitation patterns are linked with a range of environmental variables including temperature, isolation, cloud cover and wind speed (Convey 2006). In the maritime Antarctic summer precipitation increasingly occurs as rain rather than snow (Quayle *et al.* 2003), thus becoming directly available to terrestrial ecosystems. Increased precipitation has been predicted in the Antarctic coastal zone (Budd and Simmonds 1991), and is already documented in the maritime Antarctic (Turner *et al.* 2005). There are also reports of decreasing trends in precipitation also from the maritime Antarctic South Orkney Is. (Noon *et al*. 2001), highlighting the importance of understanding trends at the local scale. As well as direct precipitation, water availability in terrestrial habitats is governed by seasonal snow and glacial melt. Rapid rates of glacial thinning and retreat and loss of 'permanent' snow banks observed at a range of maritime Antarctic sites are particularly significant in this context. Such decreases are documented along the Antarctic Peninsula and Scotia Arc (Fowbert and Smith 1994; Fox and Cooper 1998; Vaughan et al. 2001; Quayle et al. 2003). While increasing the input of water to terrestrial ecosystems, earlier or increased melt may also exhaust reserves of ice or snow before the end of the vegetation season, hence locally increasing water stress on terrestrial biota. If warming increases the frequency of winter thaws, it may encourage formation of a sub-snow ice layer on the ground surface (Arnold *et al*. 2003). This process may have negative effects on some soil faunal communities. In the longer term, loss or seasonal exhaustion of itself brings another limitation to terrestrial habitats (Convey 2003).

Ice sheet fluctuation: Over recent decades the catastrophic collapse of coastal ice shelves around the Antarctic Peninsula has been observed (Vaughan and Doake 1996). The immediate consequences of this collapse are probably minimal for terrestrial biology (Convey 2006).

Ozone depletion and ultraviolet radiation: The anthropogenically generated 'ozone hole' that forms annually in the austral spring over Antarctica has been observed only since the early 1980s (Farman *et al*. 1985). It is caused by increased penetration of biologically damaging shorter wavelength UV-B radiation. While maximum intensities of radiation received under the ozone hole are similar to normal summer maxima, they differ in two important features: in the fact that maxima now occur earlier in the season (in particular, when biota may not be fully physiologically active and able to respond) and that lower wavelengths penetrate to the ground level than it is normal at this time of year (Frenot *et al.* 2005). The potential impact of the increased UV-B radiation is also modulated by other environmental conditions, such as cloud cover and type, albedo and solar angle (Sabburg and Wong 2000). At the microhabitat level even the thickness of snow layers is important (Cockell *et al.* 2002).

THE DIRECT HUMAN IMPACTS

The Antarctic is not isolated from human-related global changes (land use change, pollution, invasive species and atmospheric change). Contemporary environmental changes, including both "global warming" and the separate process of stratospheric ozone depletion (King 2005) can be seen as examples of anthropogenic processes having an indirect, consequential impact on Antarctic biota (Bargagli 2005). It is also clear that human activity since the discoveries of the various Southern Ocean islands and the Antarctic continent has had various direct impacts on their terrestrial ecosystems (Frenot *et al.* 2005, Convey 2006). On the scale of biological time, Antarctica has only very recently received visits by human, and these in relatively small numbers.

Alongside a considerable expansion of scientific expeditions and their supporting logistics, as well as a remarkable increase of tourism and non-governmental activities, the environmental conservation of Antarctica is now becoming an urgent issue (Campbell *et al.* 1994). There are a significant number of tourists visiting the Antarctic, particularly the Antarctic Peninsula, but governmental personnel remain there considerably longer and therefore have the opportunity to create considerably greater impacts on the terrestrial ecosystems (Chwedorzewska and Korczak 2010). It has never been doubted that Antarctic station operations have always been accompanied by local environmental problems (Campbell *et al.* 1994). A substantial growth in scientific expeditions resulted in the setting up of numerous stations, settlements, camps and field refuges in Antarctica. Most stations and bases have a high probability of causing adverse influences on the terrestrial ecosystems due to their localization – often at coastal ice-free areas, which are also favourable to biological communities. There are a few records on radionuclide or trace elements contamination at the neighbourhood of the big Antarctic Stations (Mietelski *et al.* 2008).

Also, more and more evidence has been found that the Antarctic is receiving a steady biological import from other parts of the world in various ways. It is suggested that there is no or very rare passive initial introduction of alien species by natural vectors. However, humans appear to be responsible for the dispersal of alien organisms as a result of such activities as the importing of poultry products (Chwedorzewska unpublished data), and the introduction of non-indigenous plants (Olech 1996; Chwedorzewska 2008) and animals (Pugh 1997). As is the case with the native biota of Antarctica, the knowledge of the non-indigenous biota is at best patchy – vertebrates and vascular plants are relatively well documented, while the knowledge of arthropods and other macro- and microscopic invertebrates varies widely between locations, depending on the availability of expertise. Cryptogams and, in particular, microbial groups have largely not been addressed (Cowan and Ahtow 2005). However, the current changes in the climate conditions might modify the status of several alien species. Climate amelioration could influence the status of species that apparently have a small impact and could increase their competitive abilities, making them dominant in the communities (Frenot *et al.* 2001).

CONSEQUENCES OF CLIMATE CHANGE FOR BIODIVERSITY

Climate change has already produced significant and measurable impacts on almost all ecosystems, taxa and ecological processes, including changes in species distribution, timing of biological behaviours, assemblage composition, ecological interactions and community dynamics. Species have evolved over millions of years to adapt to specific climatic conditions, as well as to variations in climate, but the current increase in temperature and differing weather patterns have occurred over an extremely short period of time, which evolutionary processes are not able to match. Therefore, many species of plants and animals are not able to adapt to the changing temperature and weather (Bargagli 2005).

The consequences of climate amelioration are generally expected to include increased terrestrial diversity, biomass and trophic complexity, all of which contribute to more development of more complex ecosystem structure and an increase in the importance of competitive interactions and abilities (Convey 2006). At the simplest level, changing patterns of climate will alter the natural distribution limits for species or communities. In the absence of barriers it may be possible for species or communities to migrate in response to changing conditions. Vegetation zones may move towards higher latitudes or higher altitudes, following shifts in average temperatures. Movements will be more pronounced at higher latitudes, where temperatures are expected to rise more than nearer the equator. In many cases further complications will arise from the complexity of species interactions and differential sensitivities to changing conditions between species. Certain species may rapidly adapt to new conditions and may act in new competition with others. Global climate change creates conditions that may be suitable for some invasive species to become established in new areas. Antarctic terrestrial ecosystems, through their general simplicity of structure, are predicted to show particular sensitivity to environmental change (Convey 2003). Consequences at ecosystem level are wide-ranging rather than restricted only to the directly impacted taxa. A community or ecosystem's direct response to environmental change *in situ* becomes separated from responses involving long distance colonisation by alien taxa (Chwedorzewska 2008, Olech 1996). The ameliorating growth conditions provided by the rising of maritime Antarctic temperatures increase the threat of invasion by alien species in this region. Evidence has shown that there is a continuous immigration of sporomorphia from South America (Lewis Smith 1984, 1991) and exotic pollen and spores have been detected on Antarctic islands and also on the continent. Exotic pollen and spores of bryophyte and lichen species have been detected on the continent (Linskens *et al.* 1993). Particular species (Melick *et al*. 1994) and sites (Selkirk *et al.* 1997) have been identified as having greater potential for invasion. In addition to the potential for species from outside Antarctica to colonize the continent, expansion of species ranges within Antarctica is also a possibility, and few native Antarctic species have been identified as potential long-distance dispersers (Convey and Lewis Smith 1993). Combined with ameliorating growth conditions, the likelihood of colonisation by new populations of native and alien species is projected to increase under a warmer climate (Robinson *et al.* 2003). While the contemporary biota shows the ability to survive abiotic environmental extremes, competitive abilities are very poorly developed communities and species are seen as vulnerable to increased competition, including predation, from invading taxa (Convey 2003, Frenot *et al.* 2005, Chwedorzewska 2009).

The two vascular plants native to the maritime Antarctic have provided the most studied examples of measured biological response to recent environmental warming in this region (McGraw and Day 1997, Gerighausen *et al.* 2003). Some local populations have increased by as much as two orders of magnitude in as little as three decades, and there has been a change in the balance of reproductive strategy utilisation towards successful sexual reproduction by increasing the probability of establishment of germinating seedlings (Convey 1996) and also stimulating growth of the seeds that have remained dormant in soil propagule banks (McGraw and Day 1997). Also there are some records of very rapid and large responses (biomass, morphology, numbers) in bryophytes, microbiota and fauna (Lewis Smith 2001) with greatly increased populations. However, they are no less important through being subtle, as any response must require changes in resource allocation. Very subtle changes at one trophic level can integrate through communities and ecosystems to become considerably more significant to other organisms (Convey 2003). While over 200 non-indigenous species are already documented as having become established in Antarctica (Frenot *et al.* 2005), the large majority of these relate to the sub-Antarctic islands. In these locations there are now many examples supporting the prediction of vulnerability of native biota to stronger competitors and predators. There is currently only one analogous example amongst the few species to have become established in Antarctic maritime zone: *Poa Annua*, which is already established in King George Island (Olech 1996, Chwedorzewska 2008).

Also the events of cyclic freeze and thaws are increasing in frequency (Lovelock *et al.* 1995). Those cyclic temperature fluctuations may be more damaging to plant tissue than exposure to cold temperatures alone (Kennedy 1993). Continental Antarctic species can survive repeated freeze–thaw events (Melick and Seppelt 1992), while maritime species appear to be less tolerant (Davey 1997). Tolerance of freeze–thaw events involves interactions with other environmental parameters, such as water availability (Lovelock *et al.* 1995). Reduction of snow cover due to climate warming results in Antarctic plants being more exposed to damage by freeze–thaw events. Hence, freeze–thaw cycles can reduce plant productivity and survival (Robinson 2003).

The deleterious effects of increased UV-B (280–320 nm) and UV-A (320–400 nm) radiation reaching the surface of Antarctic ecosystems. The UV-B effects considered most harmful to life include mutagenic interactions with DNA and RNA and absorption by proteins, and damage to membranes and pigments with negative effects on physiological functioning of organisms, like for example: photosynthesis and primary productivity (Karentz 1994). The potential increase of direct radiation damage to cellular components (e.g., chloroplasts and their integral chemical photosystems, DNA) (Rozema *et al*. 2002) and the associated increase in exposure to these shorter wavelengths alters the ratio of PAR or UV-A to UV-B, which is important for intracellular repair processes (Santas *et al.* 1997). Vulnerability to UV-B damage is likely to be greater in plants occurring at high latitudes due to the fact that they have evolved under lower UV-B condition (Marchant 1997). Prior to ozone depletion, polar plants were growing under the lowest UV-B level on Earth, and in the last few decades they have been exposed to a similar level as temperate plants, having little time for evolutionary adjustment and acclimation (Karentz 1991). The annual occurrence of the "ozone hole" also coincides with the time of emergence from winter dormancy beneath the protective snow cover (Wynn-Williams 1994). For the Antarctic terrestrial communities, a significant change associated with the ozone hole is not in the magnitude of UV-B exposure, but in the timing of the exposure in early spring, when organisms may be in a physiologically inactive state and unaccustomed to these levels. (Convey 2003; Frenot *et al.* 2005).

CONCLUSION

Climate changes in Antarctic are occurring throughout Antarctica, affecting three major groups of environmental variables of considerable biological significance: temperature, water, UV-B radiation, and have already impacted especially terrestrial organisms from the maritime Antarctic. Amelioration of climate has led to changes in distribution of native species, increased opportunities for alien species to invade. Increased UV-B radiation already influenced strongly plant physiology.

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