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CLIMATE CHANGE AND BIODIVERSITY IN HIGH LATITUDES AND HIGH ALTITUDES

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ABSTRACT: Present knowledge of environmental processes, and climate modelling, predict that the changes in planetary surface heat flux that appear to be in store will be greatest in high northern latitudes and in the sub-Antarctic. These effects can be expected to be further complicated in rugged mountainous districts, where the combination of low sun angle, great seasonal differences in solar energy received during winter and summer, and very uneven distribution of precipitation result in intense local contrasts in environmental conditions. Somewhat similar extreme environmental conditions prevail also in the highest mountain areas along the spine of the American Cordillera. Ecosystems that have developed in polar, sub-polar and high alpine conditions are typically low-energy systems, with relatively few species at each trophic level, and comparatively simple food chains. Individuals of the constituent species must have the ability to become dormant when conditions are unfavourable, or to migrate, sometimes over great distances. Such ecosystems, highly stressed by physical factors, commonly simple in organization but with great complexity of pattern, are inherently particularly vulnerable to rapid change in climate. They typically have evolved a delicate and complex intertrophic interdependence in which plant germination and growth, development and distribution of insects and other invertebrates including parasites and microfauna, and the life cycles and behaviour of vertebrates, each with a distinctive response and maturation period, are marvellously interlinked. Any rapid or significant change in climate is likely to disrupt this interlocking system and affect the biological diversity. A warming climate will also likely introduce new species from lower latitudes and altitudes, further disrupting the ecosystem. Human activities that affect the global climate and environment have distinctive consequences for the ecosystems and biological diversity of high latitudes. Among the serious effects are enhancement of ultraviolet-B radiation and concentration of toxic contaminants from the long-range transport of air pollution. Some of these characteristics and problems are being studied through the International Tundra Experiment (ITEX); the Zackenberg Ecological Research Operations (ZERO) in Greenland; at the Toolik Field Station in Alaska; and through the UNESCO MAB Global Change in Mountain Regions (GLOCHAMORE) network of Biosphere Reserves; while others are topics in the research of the current International Polar Year (IPY).

Keywords: climate change, biodiversity, altitude, latitude, elevation

1. Introduction

Much of the international research and monitoring activity dealing with the evidence, causes and consequences of changes in biological communities is focussed on biological abundance and complexity. Most studies and discussions of biological diversity are concerned with regions that are biologically rich, with large numbers of interactive species and complex ecosystems. But "The Americas", which extend over 14,000 kilometres and one hundred and forty degrees of latitude, from Kaffeeklubben Island at 82 degrees North Latitude to Diego Ramierez Island at 56 degrees South Latitude, contain lands of less biological abundance. In the high latitude portions of this extensive land mass and coastal area, environmental conditions are such that biological productivity is limited, and ecosystem complexity and diversity is low compared to that of lower latitudes. Because of the limited number of species and pathways of intertrophic interactions in such areas, the local and regional ecosystems are proportionally more sensitive to changes in species diversity.

At the same time, planetary geography and the current pattern of distribution of surface heat by atmospheric and ocean circulation is such that, for a given change in the overall global climate, both the absolute and relative changes in climatic conditions will be greatest in high northern and southern sub-polar areas. The relatively impoverished high-latitude biological systems, already inherently sensitive to changes in climate, will from present knowledge be subjected to the greatest disturbance from the climate changes that appear to be in store for the planet.

Current evidence of such sensitivity, although mostly observational and unconnected to coherent interpretation, is abundant - the plight of undernourished polar bears because the decrease in seasonal sea ice has reduced coastal marine productivity; the replacement of woodland caribou range by moose habitat in the sub-arctic because of the northward migration of shrub vegetation; and the disruption of the “traditional” timing and routes taken by migratory caribou are examples.

In a somewhat analogous fashion, the great Cordilleran chain that stretches from Alaska to Terre del Fuego contains many high peaks and plateaux even in lower latitudes where the environmental conditions are too harsh to support vegetation and its associated animal life in the abundance and diversity of that found nearby at lower elevations. In these areas also, small changes in biological diversity, from whatever cause including climate change, can have severe ecological consequences.

It is therefore important to recognize that changes in biological diversity due to climate change are equally, if not more, important to ecosystems that are already stressed by physical conditions and where species numbers are low, as they are in biologically rich areas. Research and monitoring in these environmentally harsh and deceptively “simple” areas may tell us much about the characteristics and the biological consequences of climate change and global change (Price *et al.*, 1994; MacIver *et al.*, 1994; Chapin and Korner, 1995).

2. Environmental characteristics of high latitudes and high altitudes

The distinct environmental characteristics of high latitude regions are first of all a consequence of the shape of planet Earth, its axis of rotation, and its orbit around the Sun. Because of the tilt of the Earth's polar axis, the Sun, as seen from the Earth's surface at higher latitudes, appears to be "lower" in the sky, and the amount of solar energy received on each square meter of land or sea is less. The average solar energy received on the Earth surface near the equator is about 140 watts per m^2; at 65 degrees north or south about 25 watts per m^2. Although in high latitudes solar energy is received at an oblique angle, the Earth radiates energy perpendicularly to outer space, as it does from every other part of the surface of the planet. There is thus a net loss of energy from high latitudes, mainly in the form of long-wave radiation from the tops of clouds and layers of ice crystals in the stratosphere. This loss is made up through the transport of heat from lower latitudes by atmospheric circulation and ocean currents. The thermal balance between incoming and outgoing energy is achieved in the Polar Regions at a surface temperature considerably lower than the planetary average. The average year-round temperature at the North Pole is today 56 degrees Celsius lower than it is at the Equator (the difference is even greater at the South Pole because of altitude, and other variables).

Furthermore, the tilt of the axis of the spinning planet with respect to its orbit around the Sun (at present about 23.5 degrees) has the result that seasonal differences in net energy at the surface – summer in the hemisphere where the polar axis is tilted toward the Sun, winter when it is tilted away – are progressively greater at higher and higher latitudes. Not only the intensity, but also the period of solar insolation and illumination changes dramatically with latitude. At the Poles themselves, of course, solar illumination, although weak, is continuous for six months of the year in summer, and no direct solar energy at all is received during the alternate six months.

These features make the regional climate at high latitudes very dependent on the transport of heat from low to high latitudes in both hemispheres by atmospheric and ocean currents, and on the heat trapping capacity of clouds and greenhouse gases. Thus, changes in the energy balance and energy circulation for the planet as a whole have a much greater effect on the energy available for biological life in polar and sub-polar regions than the planetary average (Roots, 1989b).

The planetary architecture, the pattern of continents and ocean basins, also has an important influence on the transport of heat from low to high latitudes in each hemisphere, and accounts for much of the difference between the climate of North America and South America at equivalent latitudes. The long north-to-south shape of the American continents acts as a major barrier to the east-west ocean and atmospheric circulation generated by the Earth's rotation, while the clustering of continents in the northern hemisphere and the relatively open round-the-planet west-to-east transport of heat by the Southern Ocean are major determinants of the pattern of world climate. Thus, in North America, the strong south-to-north heat transport in the Atlantic Ocean off its eastern coast serves to warm the lower temperate latitudes, but as the north-flowing Gulf Stream current veers to the east it pulls very cold water and air from the Arctic Ocean basin southward along the east coast, giving that part of the continent anomalously low temperatures. On the west side of North America, circulation of the relatively cool North Pacific Gyre stabilizes the climate of the coastal areas, with an observed decadal oscillation of winter temperatures and precipitation, but provides moisture for the whole northern high latitude region. Quite small variations in this complex system, including those resulting from human-caused influences on the penetration and reflection of solar energy in the atmosphere, have potential to make significant rapid changes in the regional climate.

The climate of the southern part of South America is dominated by the relatively cold south-flowing ocean current along its west side and the turbulent water and air energy mixing of the Drake Passage, where the strong east-flowing circumpolar Southern Ocean is forced through a six-hundred kilometre-wide gap, with associated confused and variable circulation on the eastern side of the continent and some of the highest-energy atmospheric turbulence found anywhere on the planet. The very vigorous atmospheric and ocean energy system in this region has some characteristics similar to those found in the northern hemisphere at relatively higher latitudes; but the turbulence is such that the rapid climate changes which are seen to be ecologically significant in the northern hemisphere would for the most part appear likely to be lost in the "environmental noise" off South America.

The net environmental effect of these energy characteristics at high latitudes is that water in the air, on the surface of the land or ocean, and in the ground is commonly, frequently, or periodically in the solid state (Shulski and Wendler, 2008). Ice and snow on land and waters, permafrost or frozen ground, and ice crystals in the atmosphere are typical. The land is snow-covered, and lakes and rivers are ice-covered, for several months of the year. Much of the surface-to-air heat flux, already weak compared to that typical of lower latitudes, is involved in phase change from liquid water or water vapour to ice or snow crystals and back again without change of temperature. Because biological life as it has evolved on Earth requires liquid water for cell growth and reproduction, the conditions for life in high latitudes are still further restricted.

Global and regional models of climate, based on data of recent and current temperature and precipitation and present knowledge of the characteristics of land/ocean/atmosphere energy fluxes, vary among themselves depending on the assumptions made and scale simplifications, but all are consistent in indicating that the expected net warming in sub-arctic and arctic latitudes will be four to six times the global average for any plausible scenario for planetary climate change. The warming is predicted to be greatest in winter, with indicated temperatures for November to March in inland North America at Latitude 65 degrees North as much as 12 degrees Celsius higher than the average of the past century. Such changes would radically displace the timing and importance of the liquid water/ice phase change, affect snow cover, river and lake ice, the stability of frozen ground, and a range of coastal and marine processes (Weller, 2000).

At high altitudes in the American Cordillera, rugged topography exacerbates the local net heat changes and results in extreme local contrasts in micro-climates. Solar insolation, exposure to wind, and cloudiness may vary drastically within distances of a few hundreds of metres, resulting in extreme differences in diurnal and seasonal temperatures, and local variations in precipitation, accumulation of snow, and of water storage, run-off, or frozen ground (Beniston, 2003). Small changes in regional climate, superimposed on the complex and heterogeneous patterns of local physical environments in high mountainous areas, may trigger large changes in local hydrology, soil moisture, and land stability (Luckman and Kavanagh, 2000; Allard *et al.*, 2002). Such areas are difficult to model or monitor from a climatic aspect, but as they are essential sources of water for human use and life support at lower elevations throughout much of the Americas, knowledge of the sensitivity of high alpine areas to climate change is very important (Roots, 1993; Grabherr, 2005; Bradley *et al.,* 2006).

High altitude areas or plateaux that are not locally rugged are relatively restricted in the Americas. The altiplano of central South America is the type example. These areas commonly experience low average temperature similar to some sub-polar lands, but diurnal and seasonal patterns of solar energy are typical for their latitude. Although data are sparse, it appears that the increase of temperatures experienced by nearby lowland areas in recent decades have been as great or even exaggerated in the higher regions and mountain slopes above the forest limit. Many of the major glaciers are shrinking alarmingly, the duration of seasonal snow cover is reduced compared to the average of the past two centuries, and the meltwater from ice and snow areas, which provides much of the moisture for rivers, forests, and lowland agriculture, is reduced (Bradley et *al.,* 2006; Lugo *et al.,* 2004; Ramierez, 2003).

Throughout much of the Cordillera, glaciers have been shrinking conspicuously for the past half century (Young, 1985; Williams and Ferrigno, 2002; Adam, 2006; Kasser, 2007).

3. Ecological Characteristics of High Latitudes and High Altitude Terrain

There are many definitions and proposed criteria to designate high latitude and high altitude areas from an ecological aspect, but a convenient one for the present discussions refers to areas or terrain where the average annual surface energy flux is not sufficient to maintain the production of erect woody plants, even in the presence of liquid water. Such areas are popularly recognized as "beyond the tree-line". Although the tree-line may be convoluted and with anomalous outliers, and although in the past it has shifted with changes in climate, it usually is clearly recognizable, and marks a genuine ecological boundary (Begin *et al.,* 1999; Danby and Hik, 2007). Areas beyond the northern tree-line that carry a vegetative cover are commonly called tundra; areas still further north or higher, where bare ground predominates over macroscopic plant cover, are referred to as polar desert (Bliss, 1998).

Beyond the tree-line, the low prevailing temperatures, limited periods of liquid water, and interrupted solar radiation result in slow weathering of rocks and soils compared to that typical of temperate or tropical areas, so that there is consequently a slow release of soluble nutrients essential for plant growth. Bacterial action in a treeless tundra may be two orders of magnitude slower than that in a flourishing forest in the temperate regions. These basic factors, which underlie the productivity and vigour of the whole ecosystem, are clearly a direct result of climate conditions (Billings, 1974). But how sensitive the microbiota of high latitude and high altitude soils are or will be to rapid changes in climate is little known (Heal *et al.,* 1998).

Ecosystems that have evolved or survived in polar, sub-polar or high alpine conditions are typically low-energy systems, with relatively few species at each trophic level compared with ecosystems elsewhere (Huber *et al.,* 2005). Arctic marine ecosystems are likewise comparatively simple compared with those of lower latitudes (Muir *et al.,* 2002). Food chains tend to be simple and short. The continuous solar radiation during the brief summer results in a surge of biological productivity during a short period after which growth may be very low or zero (Brown *et al.,* 1980; Zhou *et al.,* 2001). Organisms and communities have developed a number of stratagems to cope with low biological productivity or periods adverse to life (Sorensen, 1941; Molau, 1993; Jonasson *et al.,* 2000). Some, with limited mobility, are widely scattered (individual plants may be spaced far apart on bare ground and arranged in systematic patterns to gather nutrients from a large area); others cluster in limited fertile "niches" from which they expand when conditions improve. Many plants develop extensive almost impregnable seed banks (McGraw and Vavrek, 1989). Dormancy, and the ability to remain viable when metabolic rates drop very low and then revive quickly upon thawing, is an important characteristic for many species (Somme and Block, 1991). For animals with individual mobility, such as some birds, mammals, and fishes, seasonal migration to areas with more abundant food and less harsh environments for part of the year is a successful strategy (Calef, 1981; Stirling *et al.,* 1999; Reale *et al.,* 2003).

Except for the lichens, these marginal conditions for life have by and large inhibited the development of symbiotic linkages between species, so that in comparison with many other parts of the world, biological communities in high latitudes appear to be simple. The species diversity is low, compared to most other terrestrial ecosystems. Such communities, stressed more by physical factors than by biological competition, are inherently sensitive to changes in climate. For example, survival and fertility of isolated populations of alpine rodents vary with fluctuations in climate (Morrison and Hik 2007). There is evidence however that under such stressed conditions, there may be considerable genetic variation within species (McGraw, 1995; Matveyeva and Chernov, 2000). Perhaps because of this, high-latitude ecosystems have proved to be very tough. Such ecosystems in high latitude and high altitude areas rarely reach optimum stability, but are characterized by fluctuation between remarkable abundance and scarcity or near-extinction of critical species. The limited diversity of species in a given area in these regions may be conspicuously reduced by a rapid change in a particular climatic parameter; but because the ecosystem is already impoverished and a "survivor" of harsh environmental conditions, the overall longer-term effect may be less than in some biologically richer areas (MacLean, 1975; Chapin *et al.,* 1996).

Climate change that results in higher ambient temperatures will increase available liquid water and the release of nutrients (Crawford *et al.,* 1995). In winter it will affect snowfall, length of snow cover, and runoff in complex ways (Kudo, 1991). Higher temperatures during the plant growth season will enhance microbiological activity and plant metabolism (Inouye and McGuire, 1991) and also the activity and reproduction of invertebrates, including parasites and migrant species (Kevan,1972; Kukal, 1990; Inouye *et al.,* 2000). Although warming is normally expected to be associated with increased carbon dioxide in the atmosphere near the surface, the biological significance of a change of carbon dioxide concentration appears complex (Skre, 1993; Kane *et al.,* 1996).

Simple changes in weather, due to changes in climate trends, may have unexpected effects on the inter-species relations and thus on diversity. A current apparent example is the increase in late-winter snowfall on some mountains on the northeast side of the Saint Elias Mountains in Yukon, which is popularly and reasonably attributed to warming of the winter climate. The increased snow and milder temperatures have meant that high-altitude grassy slopes which in past decades were bare and windswept in early spring and provided essential forage for mountain sheep are now inaccessible to the sheep; the sheep are starving. The wolves which normally prey on the sheep in the spring appear also to be starving and if some survive, may not have energy to breed. The subsequent effect in the coming summer on the rodent population, for which the wolves are a main control, can at this stage only be speculated. If the rodent population is not checked by the wolves, the rodents are likely to over-graze and destroy their habitat. Thus climate warming on the high mountain slopes may have the result of decreasing the biological diversity and richness of the larger region.

Perhaps the most critical aspect of the potential effect of rapid climate change in high latitude and high altitude areas relates to the disruption of food chains and inter-trophic connections because different species and communities respond at different speeds to a given change in climate conditions (Murray and Miller, 1982; Hobbie, 1993). Because food chains are relatively simple, with few alternative species at each trophic level compared with the many pathways available in most lower latitude ecosystems, it is possible to observe and describe the effect of climatic variations in an instructive manner (Grabherr *et al.,* 2001; Korner and Spehn, 2002).

An example, again from the mountains of the Yukon, may serve as an illustration. The wildlife in the region is dominated by a massive herd of caribou, at present numbering about 130,000 individuals that breed annually on the Arctic Ocean coastal plain, which is fertile for a brief period in summer. The animals then migrate through the mountains and valleys to wintering grounds near the boreal forest tree-line, returning again in the spring. The herd thus undertakes an annual round trip of more than 3500 kilometres (Heuer, 2006). Its numbers are at the limit of the carrying capacity of the region. The routes and timing of the migration have evolved to take advantage of forage and presence of parasites along the way, under recent climatic conditions. After giving birth on the costal plain in early summer, the females and young move southward along the river valleys, feeding on rich early vegetation while the snow on the higher slopes melts (Lapiere and Lent, 1977; Russell *et al.*, 1992). By the time the forage in the lower valleys is nearly exhausted, insect parasites hatch by the billions, and drive the caribou to higher windier areas to escape their tormentors. By this time in most "normal" years, the substantial forage on the upper slopes will have grown and matured and be able to support the herd as it continues south (Russell *et al.*, 1993). However, periods of anomalously warm early spring weather in the last few years, which might be a harbinger of climate change and might at first be thought to be a benefit to the caribou, have only increased their hardship. The early spring has increased the warmth and snowmelt in the lower valleys, but increased the snow depth in the mountains. The result has been that insects, able to respond more quickly than vegetation to a change in climate, have hatched abnormally early in the lowlands, and driven the caribou with their still malnourished young to higher elevations, where because of excessive snow depth plant germination has been delayed and the forage consequently not developed enough to enable the females to produce enough milk to feed their young on the long strenuous migration. Much of the entire huge herd appears to have been debilitated and weakened because of "favourable" climatic conditions in early spring (Russell, 1993).

Similar complex stories of the ecological effects of the changing climates may be expected (Hinzman *et al.*, 2005). It remains to be seen how the biological diversity may be affected (Fry, 1993; Jeffries *et al.*, 1994). There are useful indications from the past, of the links between climate and biological activity in northern regions (Callaghan *et al.*, 1989; MacIver and Meyer, 1998; Rhemtulla *et al.*, 2002). Examples are "anomalous" islands of flora from the Pleistocene Beringia biological invasion which have survived deglaciation events and have then served as oases for recent plant and invertebrate colonization; the growth rings of arctic heather *cassiope tetragona* clumps which are more than a century old and which show decades of slow growth and periods of vigorous growth; timberline trees in Vancouver Island and in Jasper Park in the Rocky mountains which reveal recurring periods of slow growth or death followed by enhanced growth that appears to reflect a climate control; the shrinkage of perennial snowbanks in the lee of mountain ridges in southwest Yukon which has uncovered remains of caribou herds that are not present in the area today (Kuzyk *et al.*, 1999) and human hunting artefacts, indicating different climates and ecosystems 3,500 to 1,000 years BP.

An obvious and often described characteristic of the biological systems in high mountains and high latitudes is that the ecosystems are zoned in response to progressively harsher physical environments. The successive biological zones reflect the climatic gradient from tree-line to arctic desert (Edlund, 1990; Matveyeva and Chernov, 2000) or to highest alpine peaks Breymeyer, 1995; Svoboda and Henry, 1987; Roots, 1993; Seig, 2004).

Plants, with limited individual mobility, express the zoning best; the common succession from trees to small bushes to distinctive arctic or alpine grasses and flowers to mosses to lichens is the standard ecological background to all descriptions and considerations of arctic and alpine areas (Billings, 1997; Levesque *et al.,* 1997). In general, each higher or more northerly zone is more impoverished than the one below it or to the south (Breymeyer, 1996). It contains fewer species, more widely separated plants, and lower living mass; yet because of slow organic decomposition the net biomass may be as great or greater than that at lower latitudes or altitudes (Edlund, 1992; Jonasson *et al.,* 2000).

One common characteristic of plants in more and more difficult living conditions is that a progressively higher proportion of the living tissue is found beneath the surface. At Latitude 80 degrees North in the Canadian Arctic as much as 85 percent of the living matter is below ground (Edlund, 1988; Oechel *et al.,* 1993). Studies of biodiversity in extreme environments must take into account the "subterranean" living component.

Any change in climate that leads to more favourable conditions for growth will of course result in biological response that could shift the vegetation zones (Walker, 1995; Sturm *et al.,* 2001; Cueva, 2002)). The rapidity with which established plant species or communities can adjust to more favourable conditions, compared with the rapidity of environmental change that might be imposed, is not well known (Hengeveld, 1989; Oechel, 1994; Lescop-Sinclair and Payette, 1995); but because high altitude and Arctic plants grow slowly compared to related species in lower altitudes and latitudes - in some cases single plants may take several years to complete a bud-to-flower-to-seed cycle that normally is accomplished in a single year in warmer conditions (Kudo 1992;

Shaver 1992)- it is not unlikely that the ecosystem will become disrupted by a rapid change of climate. Such conditions could also favour the invasion of species from lower latitudes and altitudes, which could not have survived in the colder climate. The biological diversity would be changed (Danby *et al.*, 2003).

4. Effect of human activities on the climate and environment of high latitudes and high altitude terrain

The effects of human activities on the climate and environment of high latitude and high altitude terrain, with the possible consequences for biodiversity, may be considered under three main, but partly interlocking, topics: those effects resulting from activities at a considerable distance or global in nature; effects from activities within the high latitudes or in the high mountains; and those matters of special interest to resident indigenous people.

We are not concerned here with human activities that may or may not be involved in the causes and patterns of broad changes in the global environment or climate, which of course affect high latitude and high altitude areas just as they do other parts of the world. An exception is the relative increase in ultraviolet-B (UV-B) radiation, which is and will continue to be relatively greater in high southern and high northern latitudes because planetary upper atmosphere thermochemical processes, influenced by human activities, result in a greater depletion of stratospheric ozone in the polar regions, and consequently less effective screening of solar ultraviolet radiation. The effect of increased UV-B on high latitude ecosystems is imperfectly known, but research to date in the Arctic and the Antarctic indicates the possibility of severe disturbance in plant seed production and rates of growth, reduction of fertility, and damage to tissues and sense organs in animals. The short or long term effect on biodiversity may be important (Correll, 2004; ACIA, 2004).

The local or regional effect of changes in climate likely affected by human activities that is of direct concern in high latitude or mountain areas is related to changes in water supply. Argentina has taken direct legislative action in this regard. In October 2008 the Chamber of Senators passed a law that establishes a minimum budget *"for the protection of glaciers and the periglacial environment, to preserve them as strategic reserves of water resources and the critical recharging of hydrological basins"* (Villalba, 2008). In Bolivia, the shrinking of winter snowbanks has already resulted in severe water shortages and failure of irrigated agriculture (Peredo-Videa, 2009). In Canada, shrinkage of glaciers and snowpack in the Rocky Mountains is a major factor in the diminished flow of the Athabaska River, leading to serious concern about the adequacy of water to develop and process the bituminous sands of northern Alberta, a major petroleum resource. Indications are that the shrinking will continue.

Of important concern to biodiversity in the context of human activities and climate change in high latitudes and at high altitudes are the effects of far-travelled pollutants from industrial and urban activities (Barrie *et al.,* 1992; Crawford, 1997). The processes and effects of the Long Range Transport of Air Pollutants (LRTAP) have been well studied.

Volatile organic compounds (VOC's), airborne trace metals, and radioactive material attached to airborne particulates can "leap-frog" from industrial sources to high latitudes by successive volatilization, transport and deposition, and revolatilization, after which they may enter the food chain of terrestrial, aquatic or marine animals and be progressively concentrated (Macdonald *et al.,* 2002), The result can be that mammals, birds, and fish in northern latitudes may have body burdens of toxic substances considerably higher than those in animals living closer to the sources of the pollutants (Muir *et al.,* 1992; Thomas *et al.,* 1992). The enhanced level of contaminants in animals used for food is also a serious human concern (Kinloch *et al.,* 1992). The effects on the arctic plants and animal life can include inhibition of reproductive processes with consequent loss of genetic diversity, reduced growth rates, and severing of the linkages between various trophic levels (that is, dislocation of the food chain) (Rapport *et al.,* 1997; Taylor and Pitelka, 1992; Lockart *et al.,* 1992). The biological diversity will be affected.

It is difficult to separate the specific effects of the change in concentration of a single contaminant through the observation of the "health" or debilitation of a natural ecosystem in arctic or alpine areas. Most of the specific information on the effects of contaminants comes from experimental or captive studies of individuals. Such studies cannot account for the complex of stresses and changes in the natural environment. For example, present evidence shows typically a higher concentration of organochlorides in the eggs of peregrine falcons that nest in the Arctic than in nests of the same species in more southerly latitudes. Hatching success appears to be lower, but samples are too few to support firm conclusions about the relationship between contaminant concentration, other changes in the environment, and long-term falcon populations. Similarly, as is well known, the liver and other tissues of polar bears in the eastern Canadian Arctic and western Greenland carry pesticide residues and heavy metals in amounts that are far above those levels considered "safe" for large mammals, and most bears are underweight and not healthy today. But how much of their debility is directly due to contaminants from industrial sources, and how much to decrease in food availability because of changes in sea ice and other ocean conditions that may be the result of climate change cannot be determined.

The effect of further rapid changes in temperature and precipitation on the diversity of biological communities in high latitudes and high alpine areas that are already subject to stress from marginal living conditions needs careful study. It may be that the typical ecosystems in these areas are already more resilient to rapid environmental change than most of those in lower latitudes; or it may be that additional rapid climate change could trigger severe breakdown and disruption of the system, with significant loss of biodiversity (Urbanska, 1997; Martin and Hik, 2002).

Land use for agriculture beyond the tree-line is found in the Americas at present only in the high Andes. Here, pasture and crop land, typically let fallow for long periods between croppings, provide opportunity to observe the processes and rates of changes in biodiversity (Canon, 2003; Sarmiento, 2004). The history of the raising of livestock in Greenland during a period of more benign Arctic climate, and current studies of recovery of disturbed lands near present settlements are instructive examples of biodiversity change in the Arctic (Strandberg, 1997).

The effect on the environment and biodiversity in high latitudes or high altitudes from local or nearby human activities other than pasturing animals is confined to disturbances by settlements, ports, pipelines and transportation corridors, airfields, mines, and from subsistence or sport hunting. There are very few large human settlements north of the tree-line in North America or at high elevations in the Andes. In all cases the disturbances due to the settlements seem to be purely local, although they may be severe on a small scale. Because the rate of organic decomposition is low, special care has to be taken, for human health reasons, with water supply and sewage. When this is successful on a local basis, it appears that the regional biological functions will not be affected. Biodiversity will be maintained. However, climate warming and associated changes in sea level, hydrology, and land stability are almost certain to cause new problems.

The marine ports in Arctic North America are in several cases also sites locally rich in marine life. Care must be taken during construction and operation of the port to avoid undue physical disturbance or pollution which could seriously affect the marine ecosystem and productivity. The problem is particularly difficult for ports which are oil shipping ports or pipeline terminals (Milne, 1978). Ports in northern Alaska and Greenland provide illustrative examples. The longer term effects on biodiversity are not yet known, and the threats that may be brought to the coastal region as a consequence of changing climate, weather patterns or sea ice conditions should be watched with care. A distinctive management problem is that the ports themselves serve as centres for activities such as hunting and tourism, in a location that is biologically vulnerable but where wildlife may appear deceptively to be abundant.

Oil pipelines, with potential for environmental damage through spillage, electric power corridors, roads and airports, among others are activities which require careful and sometimes special management in high latitude-high altitude areas. Good environmental management will maintain the biological diversity. However, such facilities provide routes and may inadvertently provide opportunities for invasion by alien species during periods of climate change when conditions for biological life are more favourable. The biological diversity of the high latitude area may then be adversely affected.

Mines in the permafrost regions of North America and the high Andes constitute specific spots of land disturbance, with sometimes severe potential for pollution of the local environment. The operational period of successful mines can be expected to extend well into the time when the climate has changed from what it is at present; and this should be taken into account in mine design and all phases of its operation and closure. Environmental assessments of proposed mines should also consider likely climate change. Some examples of past damage to watercourses and coastal waters are well known, and have led to strict regulations and guidelines in Alaska, Canada, and Greenland. Care must be taken to control pollution and avoid undue disturbance of the local hydrology, particularly in the case of permanently frozen ground and ice-covered waters; but the regional biological diversity is unlikely to be affected.

A different human dimension to the issues of biodiversity and climate change in the high latitude and high altitude areas of the Americas is that of the knowledge and the concerns of the indigenous people of Arctic North America and the high central Andes. These peoples, with a very long history in the areas, who have a holistic view of inanimate and animate Nature, are very acute observers of the environment and its changes (Krupnik and Jolly, 2002; Fox, 2004) . Their myths, stories, ceremonies and patterns of living celebrate the entire biological diversity of their home regions. Many specific places both in the northern high latitudes and the high Andes are sacred or have special cultural meaning. Often the associated cultural values encompass the entire local ecosystem. Although quite different climates in the past are part of many stories and legends of the indigenous peoples of the areas (Cruikshank, 2001; 2005), the effect of impending climate change, with potential to upset the relationships between humans and the natural world that are so precious to them, may be very disturbing.

These concerns are more troublesome because in both the Arctic and the high Andes many groups of the indigenous people are not receiving full benefits from the economic and social developments of the area where they live. They are being asked to change their here-to-fore environmentally-benign lifestyle to adapt to climate changes resulting from actions in which they have taken no part.

5. Current scientific studies of climate change and biodiversity in high latitudes and high altitude terrain

Since the International Biological Program (IBP) (Bliss, 1977), there have been a large number of monitoring and research programs and individual activities recording and investigating the relationship between climate and biological systems in polar and sub-polar areas and the mountainous regions above tree-line. Some of the more significant current ones are noted below.

5.1 The International Tundra Experiment (ITEX) www.geog.ubc.ca/itex

ITEX began in 1990 as an activity within the Northern Sciences Network of the UNESCO Man and the Biosphere Program MAB, through the initiative of high-latitude researchers from the USA, Canada, Russia, Sweden, Finland, Norway and the United Kingdom, to undertake coordinated and similar studies on plants throughout the tundra biome. It has since developed into a stand-alone international scientific enterprise, involving researchers and institutions in twelve countries. It is coordinated mainly through the Department of Geography of the University of British Columbia, the University of Alaska, and the Danish Polar Center.

The initial focus of ITEX was on the response of selected typical plants with circumpolar distribution to natural variations in climate and to experimental *in situ* warming, with a secondary focus on ecosystem processes and the dynamics of tundra ecosystems (Webber and Walker, 1991). It outlined basic hypotheses and objectives for an international research program, and drew up a uniform set of protocols for standardized monitoring and measurement of ambient and microclimatic conditions and observations of plant growth and vitality (Molau and Molgaard, 1996). Techniques for standardized passive warming using small open-top plastic chambers were developed, for comparison with "unprotected" plants growing nearby (Marion *et al.*, 1993). Later, controlled amounts of carbon dioxide were introduced to some of the experimental chambers, to simulate likely conditions of a warmer climate and observe the response of the vegetation.

The ITEX studies have grown more complex and sophisticated. They now embrace research on microbiota, soil conditions, and the effect of and response to invertebrate fauna (Richardson, 2002). Sites have been added in the mountain and high plateau regions above tree-line in Europe, Asia, South America, sub-Antarctic islands, and Antarctica. There are now 49 listed ITEX sites; 17 of these are in the Americas. The focus is still on obtaining rigorous, comparable, quantitative information on the response of natural vegetation and soil communities to changes in climate.

The ITEX studies have shown the advantages, indeed the necessity, of long term observations monitoring of *in situ* plant responses to changed environments. For example, measurements of the positive growth responses in the first years to elevated temperatures and carbon dioxide concentrations have been followed, in several experimental cases, by loss of growth or reproduction in subsequent years because of increased net transpiration; and soil changes below the depth of observable plant roots have a longer-term effect than expected.

ITEX produces a newsletter, *ITEX Update,* organizes periodic workshops and summary conferences (Hollister, 1999). The findings are reported extensively in the established international scientific literature.

5.2 Zackenberg Ecological Research Operations (ZERO) www.zackenberg.dk

After careful study of candidate sites, the ZERO environmental monitoring and research station was established in 1994 by the Danish Polar Center in cooperation with the government of Greenland on the shore of a major fjord on the east coast of Greenland at Latitude 74 degrees North. The location was chosen because it was suitable for a wide range of terrestrial and coastal marine investigations in the physical and biological sciences, and also because fortuitously it was as far from known major paths of transport by atmospheric or ocean currents of pollution from industrial sources as it was possible to get in the northern hemisphere. A long-term monitoring station at this place, with associated research, could serve, as far as it is geographically possible at the beginning of the 21st century, as a "zero baseline" for continued modern observation of environmental change in the northern hemisphere.

The development of ZERO has fulfilled the expectations. A comprehensive monitoring program structure "*Zackenberg Basic*" was drawn up, supported by a consolidated data service. The observations have been continued annually, with increasing sophistication. Supplementary to the monitoring observations are separate research projects on specific subjects. About forty scientists and staff normally participate in ZERO during the field season.

Zackenberg Basic has four units. (i) ClimateBasis: meteorological observations according to a rigorous detailed program at three sites in different topographical situations; snow cover and chemistry; sea ice behaviour; permafrost and soil characteristics; river hydrology, chemistry, sediment load; carbon dioxide flux; UV-B received. (ii) GeoBasis: geomorphology and landscape monitoring along selected standard profiles from coast to upland; measurements of mass wastage; shoreline and coastal changes. (iii) BioBasis: reproduction, phenology, greening, for dominant and indicative plants (correlated with ITEX); insect and spider sampling, census, and distribution with topography; insect pollination and predation on flowers; breeding census of birds; phenology of shorebirds, waterfowl, upland species; census and behaviour observations on mammals (lemming, ermine, hare, musk-ox, fox, wolf, bear, walrus, seals, narwhal), freshwater zooplankton. (iv) MarineBasis: Sea ice; physical, chemical, nutrient, and biological profiles in fjords; sediment exchanges; oxygen and carbon cycles; benthic animals in plants near shore; body contamination of marine mammals and fish. Individual research projects at Zackenberg have ranged widely from auroral geophysics to plant genetics. Many of the studies are correlated with research at other high latitude research stations.

ZERO provides unique and comprehensive "standard" or basic information on the arctic environment and its changes, against which the observations from other monitoring sites, circumpolar or around the planet, can be related. It is particularly valuable as an observatory to record changes in high arctic biological diversity against a comprehensive long-term background of data on the physical and chemical environment, in a location that is less affected by human perturbations than anywhere else in the northern hemisphere. Over the years it will become an even more valuable environmental reference.

With the current reorganization of the Danish Polar Center (2009), responsibilities for the ZERO activities will be carried by different Danish and Greenland government departments and institutions, but the basic monitoring and research program is continuing.

ZERO produces an annual report *ZERO*, and occasional summary volumes of its research. Monitoring data are available through its website. The results of the individual researches are reported in the open literature.

5.3 Toolik Field Station

www.uaf.edu/toolik/

The Toolik Field Station was established in 1975 on the shore of Toolik Lake in the northern foothills of the Brooks Range in northern Alaska. Its stated purpose was "to study the environmental and basic ecology of the tundra and associated freshwater ecosystems and their responses to climate change and disturbance." The station has developed as a facility to support research, rather than a research and monitoring program in itself. Managed and coordinated by the Institute of Arctic Biology of the University of Alaska Fairbanks, its basic activity and long term funding has been as the northernmost station of the Long Term Ecological Research (LTER) network of the US National Science Foundation. The present facility can support up to 80 researchers, including temporary satellite field camps. Most of the researchers are from universities. In recent years, 64 universities including twelve from outside the USA, and eight government scientific programs have made use of the facility.

The studies undertaken through Toolik were at first individual, mainly short-term. Many were directed to or needed as background for assessing the ecological disturbance of the newly constructed Dalton Highway and the oil pipeline that crosses the tundra from the Arctic Ocean coast to the Brooks Mountain Range. In the course of this work, the first careful comprehensive assessments of the biological diversity of the Arctic coastal plain and the arctic mountain region were obtained. Toolik then became a focus for the continuing Arctic System Science (ARCSS) Land/Ice/Atmosphere activities, and the US Department of Energy program on Response, Resistance, Resilience and Recovery from Disturbance (R4D), related to on-going and projected energy developments in northernmost America. Pure scientific research on biological and environmental topics however has remained the bulk of the scientific activities.

In 1996 a major review of the priorities for Arctic science and the needs for and role of the Toolik Field Station for the next 20 years recommended increasing integration of the disciplinary scientific studies, attention to process dynamics at landscape and regional scales, in order to evaluate the place of the Arctic in the total Earth system. Recommended topics of attention included:- global climate change and snow/ice albedo effects on the tundra energy budget; the dynamics of carbon dioxide and methane; terrestrial and aquatic ecosystem productivity and the role of carbon and nutrient storage; river runoff and effects on Arctic Ocean chemistry, nutrients, and circulation; herbivore and plant community dynamics, especially with respect to changes in biodiversity.

The current Science Mission Statement of the Toolik Field Station is to "support field research and education that will lead to greater understanding of the arctic region and its relationship to the global environment". Much of our scientific knowledge about diversity in the terrestrial high latitudes, its past changes, and the processes that link to climatic and human influences comes from research undertaken at or coordinated with Toolik Field Station over the past thirty years. In some subject areas, the Toolik Field Station has become the standard reference and working site both for purely scientific research and studies of the applied sciences for resource developments and environmental protection policies. These, too, must take knowledge of the effects of climate change into account. An example is the Global Hierarchical Observing Strategy (GHOST) which links a permafrost active layer mapping network with a meso-scale air temperature/precipitation network and temperature/depth profiles from boreholes to develop active layer thickness calculations, and in conjunction with ZERO studies in Greenland to provide regional estimates of the impacts of global change (Nelson and Brigham, 2003).

5.4 Global Change in Mountain Regions (GLOCHAMORE) mri.scnatweb.ch/glochamore/

The GLOCHAMORE research activity is an enterprise of coordinated research planning, organized under the UNESCO Man and the Biosphere Program (MAB) and coordinated through the Mountain Research Initiative (MRI) at Berne, Switzerland. Its purpose is to develop a state-of-the-art integrated and practical research strategy to improve understanding of the causes and consequences of global change in a selection of UNESCO MAB Biosphere Reserves in mountain regions around the world. The research in accordance with the strategy will serve as a basis for defining and implementing sustainable development policies and practices in Biosphere Reserves, which will then serve as models and examples for the respective mountain regions. The research activity builds in part on the GLORIA-WORLDWIDE (Global Observing Research Initiative in Alpine Environments) activity research themes (Grabherr, 2005) and the U.N. International Year of the Mountains (Martin and Hik, 2002).

Twenty-eight MAB Biosphere Reserves, in all the major mountain systems of the planet except in Antarctica, are participating in GLOCHAMORE. Six mountain Biosphere Reserves in the American Cordillera are taking part. The interest and objectives are not only on the "above the tree-line" aspects, but on the mountain Biosphere Reserves as a whole, including the lower slopes and valleys, the natural resources, and social and cultural issues. A number of international planning workshops have been held, addressing the drivers of global change, characteristics of changes in mountain environments and ecosystems, effects on the well-being of people, and issues of adaptation to change.

The first edition of the GLOCHAMORE Research Strategy was completed in 2005 (Gurung 2006). It contains ten sections, most of which have several sub-sections, and for each sub-section there is a research goal that has been drawn up after international discussion. The major section topics are, respectively: climate; land use change; the cryosphere; water systems; ecosystem functions and services; biodiversity; hazards; health determinants and outcomes affecting humans and livestock; mountain economics; and society and global change. Section 6, *Biodiversity,* lists the following sub-sections, each with a research goal:- biodiversity assessment and monitoring; biodiversity functioning; biodiversity management; alpine community change; key fauna and flora; mountain forest structure; culturally dependent species; and impacts of invasive species. An on-line database of GLOCHAMORE research projects is available through the MRI website.

The implementation of research programs in accordance with the Research Strategy is the responsibility of the Biosphere Reserves. In the Americas, an interesting development has been the concept of a *GLOCHAMORE American Cordillera Transect,* with potential to involve Biosphere Reserves from western Alaska to the southern Andes (there are 49 MAB Biosphere Reserves along this chain). An informal Cordilleran Network of Biosphere Reserves has been formed, and international working groups on topics of special interest are developing, including one on "Biodiversity".

UNESCO MAB, the United Nations body charged with applying Education, Science, and Culture to issues of humans and their relationship with the biosphere, has reaffirmed that its World Network of Biosphere Reserves should be major learning laboratories and demonstrations for sustainable development, appropriate to the circumstances in different parts of the world, under conditions of environmental and social change. The GLOCHAMORE studies and cooperative networks will advance this objective in the world's mountain regions. Investigation and understanding the nature and processes of climate change and their relationship to biological diversity are central to the studies.

5.5 International Polar Year (IPY)
www.ipy.org/prog/

The current International Polar Year 2007-08 is the fourth major international coordinated research program in the polar regions. The previous ones have been held in 1887-88, 1932-33, and 1957-58. Each of the former ones has had a profound and lasting influence on world science. The present IPY is the largest coordinated scientific enterprise yet undertaken in high latitudes. Sixty-five countries are taking part or have submitted proposals for research projects, at present numbering in excess of 1200. The activities currently underway involve in excess of 5000 scientists, including investigations in both north polar and south Polar Regions.

This is the first IPY to include biological science and education research. The following is a selected list of project proposals which, by their title or subject category, appear to be directly related to biodiversity and the effects of climate on northern regions. Project numbers are for reference only and indicate the order in which proposals were received at the international central office. Not all have been completed as originally proposed, and some have been combined or consolidated. Details of each can be obtained by following the leads through the website above.

PROPOSAL NO.	
202	Arctic freshwater biodiversity network
133	Biodiversity monitoring
390	Biodiversity of arctic spiders
246	Biosphere-atmosphere coupling in the Arctic
72	Biological diversity network
55	Ecological response to atmospheric change
408	Monitoring human-caribou migration
120	Northern disease variability
443	Tracers of climate change

Most of the identified IPY 2007-2008 field research projects terminated at the end of 2008, but several have extended life or have led to continuing studies. Working on the results and interpretations will take several years. A number of international follow-up and data organization workshops and conferences have already been held and will continue. As in previous IPYs, all data will be openly available once the individual research results have been published. Information on the progress and data availability may be obtained through the web sites noted above. In most countries in the Americas, the national IPY committees have arranged a continuing science management infrastructure, so that the IPY momentum will not be lost.

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