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# ALTERATIONS TO PERMAFROST ENVIRONMENTS INDUCED BY CLIMATE CHANGE

## Alteraciones a los Entornos de Permafrost Inducidas por el Cambio Climático

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**Abstract**

Permafrost environments currently cover approximately twenty-five percent of the Northern Hemisphere. However current empirical and theoretical evidence indicates that much of the existing permafrost is in thermal imbalance to the warming that has occurred over the last 150 years. Long-term increases of temperature in the polar regions has already led to a thickening of the active layer and the gaseous release of the once sequestered carbon and methane tundra stores; an event which is likely to amplify the changes foreseen and experienced in natural and human environments. Permafrost degradation has resulted in the complete restructuring of ecosystems and geomorphological and hydrological patterns and processes. Such changes have led to extensive thawing, removal of discontinuous permafrost and the growth of thermokarst. Collectively, all these climatic-induced alterations in the structure of permafrost environments has had a detrimental effect on wildlife populations, human settlement and infrastructure. The former has seen a transition from terrestrial to aquatic ecosystems whilst damage to the latter has led to some areas being officially classed as natural hazard zones. Therefore research and corresponding action must be undertaken at those locations where sequestered carbon is being released in sufficient quantities to be of concern to the wellbeing of the entire planet.

**Keywords:** Active layer, Global Warming, Polar Regions, Thermokarst.

**Resumen**

Los entornos de permafrost actualmente cubren aproximadamente el veinticinco por ciento del hemisferio norte. Sin embargo, la evidencia empírica y teórica actual indica que gran parte del permafrost existente está en desequilibrio térmico por el calentamiento que se ha producido en los últimos 150 años. Los aumentos de la temperatura a largo plazo en las regiones polares ya han dado lugar a un engrosamiento de la capa activa y a la liberación gaseosa de los depósitos de carbono y el metano alguna vez secuestrados en la tundra; un evento que es probable que amplifique los cambios previstos y experimentados por los entornos naturales y humanos. La degradación del permafrost se ha traducido en la reestructuración completa de los ecosistemas y de los patrones y procesos geomorfológicos e hidrológicos. Tales cambios han conducido a un extenso descongelamiento, la eliminación del permafrost discontinuo y al crecimiento de termokarst. En conjunto, todas estas alteraciones climáticamente inducidas en la estructura de los ambientes de permafrost han tenido un efecto perjudicial sobre las poblaciones de la vida silvestre, los asentamientos humanos y la infraestructura. Las primeras formaciones han visto una transición de ecosistemas terrestre a acuáticos, mientras que el daño a estos últimos ha dado lugar a que algunas áreas sean clasificadas oficialmente como zonas de peligros naturales. Por lo tanto, la investigación y las acciones correspondientes deben llevarse a cabo en los lugares donde se está liberando el carbono secuestrado en cantidades suficientes como para ser motivo de preocupación para el bienestar de todo el planeta.

**Palabras claves:** Capa activa, Calentamiento Global, Regiones polares, Termokarst.

## INTRODUCTION

Permafrost, a layer of frozen ground which has been below zero centigrade for at least two consecutive years, is by its very nature and definition susceptible to climate change (Gouldie 2006). Like, the other environments within the cryosphere, permafrost plays a vital and central role in the changes occurring in the Earth's environment (Slaymaker & Kelly 2007) particularly as:

*Climate change in Polar Regions is expected to be among the largest and most rapid of any region* (Houghton *et al*. 2001).

Empirical evidence, supportive of this statement from the *Third Assessment Report* by the Inter-Governmental Panel of Climate Change (IPCC), strongly suggests that impacts related to climate warming are already happening in Polar Regions (Morison *et al.* 2002, Smith *et al.* 2002). Such changes include alterations to the air and ground temperature (Moritz *et al.* 2002, Majorowicz & Skinner 1997), thermal properties of the surface cover and substrate, soil moisture and snow cover (Hinkel *et al.* 1997, Paetzold *et al.* 2000). These factors heavily influence the thickness of the active – layer which accompanied by ground ice melt and the development of thermokarst can have profound detrimental effects on the regional environment (Burgess *et al.* 2000, Dyke & Brooks 2000) including the radical restructuring of ecosystem patterns and processes (Jorgenson *et al.* 2001) and adjustments to the carbon (Tarnocai *et al.* 2006) and hydrological cycles (Lawrence & Slater 2001). Geomorphological processes and phenomena are also greatly affected (Gouldie 2006) which have subsequent negative socio-economic and infrastructural consequences for vulnerable arctic communities (Jorgenson *et al.* 2001, Nelson *et al.* 2002, USARC 2003).

Furthermore and perhaps more worryingly, there is growing evidence that permafrost degradation will result in the intensification of global warming (Jorgenson *et al.* 2001) because a substantial proportion of the carbon store in the tundra is contained in the near surface layer (Ping 1996). And with Hobbie *et al.* (2000) estimating a carbon content as high as sixty percent within the soils of boreal forest and other northward ecosystems the global repercussions are bordering on catastrophic.

Due to permafrost thawing, there has also been a 22-66 percent increase in methane released at Stordalen Mine, Sweden (Lawrence & Slater 2005), a greenhouse gas (GHG) over twenty times more effective at trapping heat in the atmosphere than carbon dioxide (EPA 2008).

## PERMAFROST AS A CLIMATIC INDICATOR

Climate is the chief deciding factor in the formation and existence of permafrost. (Brown & Péwe 1973). Of all climatic factors the relationship between mean annual temperature and ground temperature is most important and thus there are correlations between latitudinal temperature and the existence, depth and type of permafrost.

Conventionally, there are two main classes of permafrost; continuous which is present at all localities except for occasional thaw zones known as *taliks* and discontinuous which is present in small scattered areas and often dependent on other factors such as relief and vegetation abundance (Brown & Péwe 1973). Continuous permafrost is typically located at colder isotherms (-7C) than discontinuous which exists at temperatures closer to zero (Gouldie 2001).

The southern limits of permafrost distribution in northern Europe have retreated 23 - 24° northward, North American cover has shrunk 16 - 18° whilst China has seen a 6 – 8° decrease since the last glaciation (Jin *et al.* 2000).

Doubling of atmospheric carbon dioxide concentration is expected to lead to pronounced reductions in discontinuous and mountain permafrost and a corresponding shift in landscape forming processes (Slaymaker & Kelly 2007). Different global circulation models (GCMs) have generated various figures but all agree that the loss in the Northern Hemisphere, where permafrost regions represent approximately twenty-five percent of exposed land area (Zhang *et al.* 2000, will be quite substantial. Anismov & Nelson (1995) calculate a sixteen percent reduction which accounts for a loss of an area $4.10^6$ $km^2$ whilst even the conservative estimation by Street & Melnikov (1990) is a sombre ten percent within the next fifty years at a warming rate of two degrees. With recent reports of 3 - 4 C increases in areas of Alaska, north of the Brooks Range (Osterkamp 2005) and an identical increase in average temperatures in Western Siberia (Pearce 2005) the loss of permafrost environments and ecosystems could be critical. At these temperature increases, continuous permafrost will also be affected, albeit over a longer time period with localised thawing, slope instability and ice wedge thawing expected (Lunardini 1996). The predicted widespread losses are likely to trigger an environmental catastrophe fuelled by accelerated mass movement, erosion and sedimentation which is amplified further via the release of damaging trace GHGs (Slaymaker & Kelly 2007).

The extent of viewable changes over a short-time period has led to frozen ground activity being designated by the IPCC as a "geo-indicator" for monitoring and assessing environmental change (Berger & Iams 1996). It has also been identified as one of the six cryospheric indicators of global climate change within the monitoring framework of the WMO Global Climate Observing System (Burgess *et al.* 2000, Harris *et al.* 2001a, Harris *et al.* 2001b). Nelson *et al.* (1993) goes one step further stating that permafrost's role in climatic change is threefold.

1) It serves as a *recorder* of climatic change and trends over long periods (Lanchenbruch & Marshall 1986).
2) It is a *facilitator* of further climatic change through the release of GHG (Rivkin 1998) and the transmission of active layer changes to the surrounding environmental components (Slaymaker & Kelly 2007).
3) It can be an effective *translator* of environmental change through its effect on natural and human communities (Williams 1995).

In cold regions many aspects of sub-aerial denudation are highly sensitive to the climate and sedimentary changes and therefore are important sources of information for historic paleoclimatic fluctuations (Harris & Murton 2005). For example, the presence of ice-wedges and pseudomorphs within periglacial stratigraphy as studied by Vandenberghe (1983), are indicative of extensive permafrost in colder periods of the Quaternary.

Both glaciers and permafrost respond to changing thermal boundaries, the latter is particularly dominated by the complex energy transfers which occur at the boundary between the atmosphere and earth surface. The scale of response by the two differs however with glaciers showing a decadal response to climate change rather than the centurial to millennial responses of permafrost (Etzelmuller & Hagen 2005).

## OBSERVED CHANGES IN THE ACTIVE LAYERS OF THE NORTHERN HEMISPHERE

Permafrost is found in the Arctic, sub-arctic, high mountain ranges and in the ice free ranges of Antarctica (Slaymaker & Kelly 2007). Approximately one quarter of the Northern Hemisphere is covered by permafrost (Zhang *et al.* 2000) which includes areas such as Siberia, Greenland Canada and Alaska.

Permafrost is also found in the Southern Hemisphere particularly in Antarctica - home to thirty-seven percent of the world's total (Bockheim & Hall 2002)- and the high mountainous regions of the Andes (Schrott 1998) and New Zealand Alps (Boelhowers 2004). However, for a number of reasons and despite containing several areas of ecologically sensitive permafrost terrain, international recognition has been limited and research scarcely documented (Boelhowers 2004). The Northern Hemisphere with research stimulated by applied problem solving in the sparsely populated but abundantly resource rich and economically important circum-polar region has received far greater attention and understanding and is thus the focus of this paper.

### Active Layer

Seasonally frozen ground, more commonly known as the *active layer* is typically a metre thick film usually above the "permanently" frozen layer of permafrost. It is an extremely important component of the cryosphere because most ecological, hydrological, biochemical and pedogenical activity occurs in this substrate (Kane *et al.* 1991). This layer is however vulnerable because changing climatic conditions have been shown to cause increases in ground temperature and a corresponding thickening of the active layer. Much of the permafrost is known to be in thermal imbalance to the present climate (Anisimov & Nelson 1997) and both empirical and model evidence indicate that permafrost degradation is in response to climatic changes of the magnitude Earth has experienced in the last 150 years.

Vourlitis & Oechel (1996) reported an annual increase of 10 - 22 centimetres of the active layer in some arctic areas between the summer months of June and August whilst Serreze *et al.* (2004) explored the ratio of runoff to precipitation and found it to be proportional to the extent of permafrost. Furthermore, Halsey *et al.* (1995) found in addition to precipitation/runoff, mean annual temperature strongly correlates to the presence of permafrost. Degradation of permafrost may also have a significant bearing on the seven percent increase of freshwater discharge that the Arctic Ocean has experienced during the last seventy years (Peterson *et al.* 2002). Other hydrological impacts include gradual or catastrophic drainage of lakes (Yoshikawa & Hinzman 2003), changes in stream water chemistry (Petrone *et al.* 2000) and other fluvial geomorphological processes (Bolton *et al.* 2000, Hinzman *et al.* 2003, Gouldie 2006.)

The reduction of permafrost therefore has a profound impact on the local environment (Burgess *et al.* 2000, Dykes & Brooks 2000) and environmental change, something which looks set to accelerate with increased evapotranspiration, drier soils and the lowering of the permafrost table becoming the norm (Kattsov & Kallen 2005). These factors are a potent cocktail of disaster particularly in icy arctic areas where human settlement exists and hazard risk is high (Nelson *et al.* 2001, Nelson *et al.* 2002). In addition to the direct consequences of the above processes, encouraged by climatic change, sequestered organic material is once again subject to biochemical decomposition by soil microbes which are responsible for the release of the two principle GHGs, methane and carbon dioxide. These two gases in turn exacerbate the warming and thawing of extensive areas of discontinuous permafrost resulting in detectable changes in the hydrological cycle, vegetation composition, ecosystem function, greenhouse gas fluxes (Christensen *et al.* 2004, Smith *et al.* 2005) and the growing number of *thermokarst* environments.

## IMPACT OF THERMOKARST ON ENVIRONMENT

The thawing of ice-rich permafrost accompanied by subsidence of a limestone or dolomite ground surface creates an uneven topography (French 1996, Embleton & King 1975) with substantial relief (Nelson *et al.* 2002) known as thermokarst.

Thermokarst develops in response to the disruption of thermal equilibrium (Turnel 2003) and as a result it is a telling physical manifestation of permafrost degradation controlled by both natural and anthropogenic action (Turnel 2003, Nelson *et al.* 2002).

Typical thermokarst features include elevated mounds known as *pingos* (*bulganniakh*) and *palsas*, sink holes, tunnels, thermokarst lakes (Brown & Péwe 1973) and patterned ground (Embelton & King 1975).

Importantly, there exists an intricate relationship between thermokarst and the environment because whilst it is created by both natural and anthropogenic processes it also serves to disrupt them.

### Natural Environment and Ecosystem

Permafrost degradation on ice-rich lowlands is leading to radical restructuring and changes in ecosystem patterns and processes. Tanana Flats, for example, is undergoing widespread transition from birch forest to an herbaceous aquatic ecosystem of minerotrophic floating fens (Hinzman *et al.* 2005).

Unfortunately the conversion from precipitation driven terrestrial systems to groundwater dominated aquatic environments is common (Woo 1992, Osterkamp *et al.* 2000) Upland sites can also be effected (Osterkamp *et al.* 1998). Thawing processes are destructive because they alter the physical foundation on which forests develop.

Individual trees unable to deal with copious water and waterlogged conditions often die. In stressful conditions whole boreal forests may be devastated and succumb to sedge meadows, bogs and thermokarst ponds and lakes (Jorgenson *et al.* 2001).

The newly created ecosystem favours aquatic birds and mammals causing the displacement of the previous inhabitants. Animal frequency, density and behaviour, especially migratory patterns, can be modified and bring further ruin to permafrost environments as a result of trampling (Mackay 1970). Vegetation (trees and mosses) and peat loss or disturbance, in the discontinuous zone is particularly detrimental resulting in the disappearance of discontinuous bodies of permafrost and accelerated thermokarst development (Brown & Péwe 1973). The same circumstances in the continuous zone, meanwhile herald a lowering of the permafrost table.

### Human Environment

Human settlements are by no means immune to the effects of climatic warming on permafrost and the active layer. Indeed, severe degradation can lead to the hazardous disruption of human activities and infrastructure (Nelson *et al.* 2002).

The potential for disruption is set to increase into the future with amplified human-induced climatic change, cyclical alterations in the Arctic oscillation and positive feedbacks caused by melting ice, which exposes bare ground and ocean both of which absorb more solar heat than white ice and snow. (Le Treut & Somerville 2007, Pearce 2005). Socio-economic changes are also likely to place more pressure on the north circumpolar region due to the discovery and increased transportation and extraction of an abundance of resources including oil (Nelson *et al.* 2002).

There are also a number of extensive settlements in this region, despite its sub-optimal conditions and these communities can be extremely vulnerable to environmental changes and permafrost degradation. The dangers surrounding thernokarst and ice-thaw are perhaps best illustrated in Siberia which has experienced two permafrost related disasters. The first in 1966 led to twenty deaths in Noril'sk when a building affected by differential thaw subsided whilst the second involved complete infrastructural collapse, including the loss of three hundred buildings, electrical power and airport runways in the city Yakutsk (the biggest city built on continuous permafrost).

The situation was so dire that in 1998 the zone affected was officially declared a natural disaster area by the Russian Government (Nelson *et al.* 2002).

Clearly the effect of permafrost degradation in urban areas cannot be underestimated because although managerial decisions are partially to blame for both tragedies there is no doubt that environmental changes induced by climatic change were predominately responsible (Anonymous 1997).

## CONCLUSION

Permafrost, despite connotations in its name is anything but permanent. In fact, by its very definition, it is extremely dependent on climatic conditions. Recent climatic warming in the last 150 years has left much of existing permafrost in thermal imbalance. Discontinuous permafrost is disappearing rapidly leaving unstable thermokarst environments in its wake. The active layer of continuous permafrost regions is thickening annually, albeit to various estimates and this is causing widespread changes in the Northern Hemisphere affecting the region's ecology, geomorphology, hydrology and socio-economics.

Currently limited research prevents a full understanding of the processes occurring in the Southern Hemisphere but it is likely that the increasing atmospheric levels of the greenhouse gases methane and carbon dioxide released from their Eurasian and North American tundra stores, as permafrost thaws, will reduce the expanse of southern permafrost.

What is absolutely beyond doubt is the need to put time and resources into Southern Hemisphere research, in addition to those areas of the Northern Hemisphere where communities and wildlife populations are at risk. Finally, corresponding action must be undertaken at those locations where sequestered carbon is being released in sufficient quantities to be of concern to the wellbeing of the entire planet.

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