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Policy Implications of Warming Permafrost

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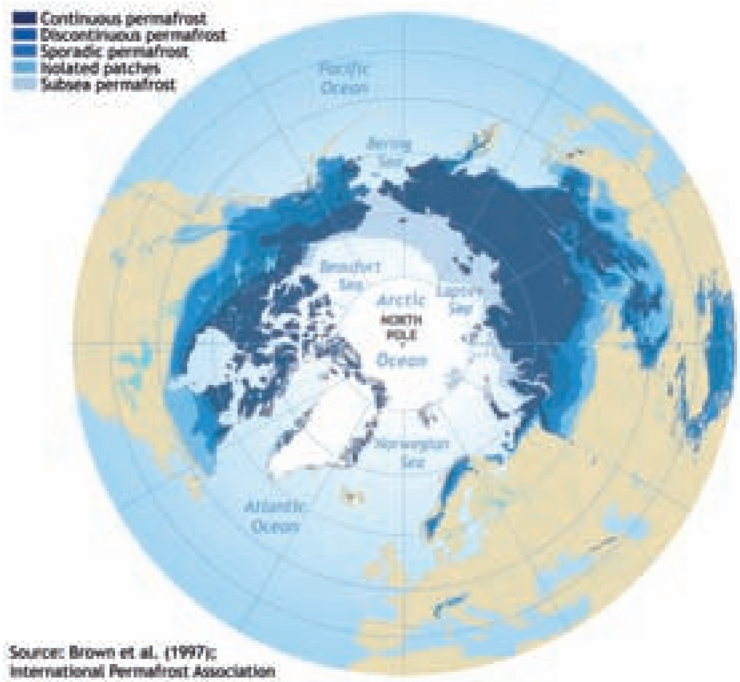
Executive Summary

Permafrost is perennially frozen ground occurring in about 24% of the exposed land surface in the Northern Hemisphere. The distribution of permafrost is controlled by air temperature and, to a lesser extent, by snow depth, vegetation, orientation to the sun and soil properties. Any location with annual average air temperatures below freezing can potentially form permafrost. Snow is an effective insulator and modulates the effect of air temperature, resulting in permafrost temperatures up to 6°C higher than the local mean annual air temperature. Most of the current permafrost formed during or since the last ice age and can extend down to depths of more than 700 meters in parts of northern Siberia and Canada. Permafrost includes the contents of the ground before it was frozen, such as bedrock, gravel, silt and organic material. Permafrost often contains large lenses, layers and wedges of pure ice that grow over many years as a result of annual freezing and thawing of the surface soil layer.



About 24% of the northern hemisphere land surface contains permafrost, divided into zones of *continuous, discontinuous, sporadic and isolated patches* of permafrost, depending on how much of the land area contains permafrost.

Two global networks monitor permafrost status: the Thermal State of Permafrost (TSP) network measures permafrost temperature at various depths in 860 boreholes, and the Circumpolar Active Layer Monitoring (CALM) network measures the thickness of the active layer at 260 sites. The active layer thickness is the maximum surface thaw depth in summer. The TSP and CALM networks are the two components of the Global Terrestrial Network for Permafrost (GTN-P), under the auspices of the Global Climate Observing System (GCOS). The International Permafrost Association (IPA) currently coordinates international development and operation of the TSP and CALM networks for the GTN-P. TSP observations indicate that permafrost temperatures have risen over the past few decades. CALM observations are less conclusive due to the melting of ice layers and lenses in near surface permafrost, but show increases in active layer thickness at many sites. Overall, these observations indicate that large-scale thawing of permafrost may have already started.

Arctic and alpine air temperatures are expected to increase at roughly twice the global rate and climate projections indicate substantial loss of permafrost by 2100. A global temperature increase of 3°C means a 6°C increase in the Arctic, resulting in anywhere between 30 to 85% loss of near-surface permafrost. Such widespread permafrost degradation will permanently change local hydrology, increasing the frequency of fire and erosion disturbances. The number of wetlands and lakes will increase in continuous permafrost zones and decrease in discontinuous zones, but will decrease overall as the continuous permafrost zone shrinks, impacting critical habitat, particularly for migratory birds. Risks associated with rock fall and erosion will increase, particularly in cold mountain areas. Damage to critical infrastructure, such as buildings and roads, will incur significant social and economic costs.

Carbon dioxide (CO_2) and methane emissions from thawing permafrost could amplify warming due to anthropogenic greenhouse gas emissions. This amplification is called the permafrost carbon feedback. Permafrost contains ~1700 gigatonnes (Gt) of carbon in the form of frozen organic matter, almost twice as much carbon as currently in the atmosphere. If the permafrost thaws, the organic matter will thaw and decay, potentially releasing large amounts of CO_2 and methane into the atmosphere. This organic material was buried and frozen thousands of years ago and its release into the atmosphere is irreversible on human time scales. Thawing permafrost could emit 43 to 135 Gt of CO_2 equivalent by 2100 and 246 to 415 Gt of CO_2 equivalent by 2200. Uncertainties are large, but emissions from thawing permafrost could start within the next few decades and continue for several centuries, influencing both short-term climate (before 2100) and long-term climate (after 2100).

Below are specific policy recommendations to address the potential economic, social and environmental impacts of permafrost degradation in a warming climate:

1) **Commission a Special Report on Permafrost Emissions:** The Intergovernmental Panel on Climate Change (IPCC) may consider preparing a special assessment report on how CO_2 and methane emissions from thawing permafrost would influence global climate to support climate change policy discussions and treaty negotiations. All climate projections in the IPCC Fifth Assessment Report, due for release in 2013-14, are likely to be biased on the low side relative to global temperature because the models did not include the permafrost carbon feedback. Consequently, targets for anthropogenic greenhouse gas emissions based on these climate projections would be biased high. The treaty in negotiation sets a global target warming of 2°C above pre-industrial temperatures by 2100. If anthropogenic greenhouse gas emissions targets do not account for CO_2 and methane emissions from thawing permafrost, the world may overshoot this target.

2) **Create National Permafrost Monitoring Networks:** To adequately monitor permafrost globally, individual countries may consider taking over operation of TSP and CALM sites within their borders, increasing funding, standardizing the measurements and expanding coverage. This applies to all countries with permafrost, but particularly to countries with the most permafrost: Russia, Canada, China and the United States. The IPA should continue to coordinate development and the national networks should remain part of the GTN-P.

3) **Plan for Adaptation:** Nations with substantial presence of permafrost may consider developing plans evaluating the potential risks, damage and costs of permafrost degradation to critical infrastructure. This applies to all countries with permafrost, but particularly to Russia, Canada, China and the United States. Most nations with permafrost currently do not have such plans, which will help policy-makers, national planners and scientists quantify costs and risks associated with permafrost degradation.

Foreword

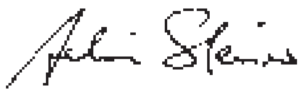
Out of the world's entire population, few know what permafrost is and fewer still have ever seen - let alone set foot upon - actual permafrost. Yet permafrost occurs in 24% of exposed land in the Northern Hemisphere. Permafrost is key to the planet's future because it contains large stores of frozen organic matter that, if thawed and released into the atmosphere, would amplify current global warming and propel us to a warmer world.

This report seeks to inform a broad audience about permafrost and communicate to decision-makers and the general public the implications of changing permafrost in a warming climate. It defines basic terminology and describes fundamental physical and biological processes that shape the permafrost landscape using the best scientific information available from published literature. The report discusses the impacts of a changing climate on ecosystems and human infrastructure in regions with significant presence of permafrost, as well as the impacts of thawing permafrost on global climate. Graphics, illustrations and photographs help explain complicated concepts and ideas in a way that is easily understood and visualized by a non-scientific audience.

This report builds upon other reports written in recent years. These reports are very technical in nature and target a limited, scientific audience rather than a broader group of decision-makers and the general public. The 2011 executive summary of the *Snow, Water, Ice and Permafrost in the Arctic* assessment report from the Arctic Monitoring and Assessment Programme focused on how climate change influences the Arctic cryosphere, rather than the other way around, and did not include all areas with permafrost, particularly alpine regions. The Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report dealt with the subject of permafrost in a highly scientific fashion under Working Group I in Chapter 4. In 2007, UNEP produced a volume entitled *Global Outlook on Snow and Ice*, where one chapter included an overview of permafrost. Again in 2008, in the *UNEP Yearbook of our Changing Environment*, UNEP devoted a chapter to methane emissions, but did not focus on permafrost. **This current report fills a gap by providing a concise, highly-readable and fully up-to-date description of permafrost and future social, economic and environmental impacts of changing permafrost in a warming climate.**

I would like to thank the team of scientific experts who have prepared this report. We hope their dedication and hard work will be rewarded by wide interest among those who can affect decision-making processes relevant to the state and trends of global permafrost.

United Nations Environment Programme (UNEP)



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Executive Director

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1. Introduction

Permafrost - perennially frozen ground - covers vast stretches of land at high latitudes and altitudes in both hemispheres. Most regions with permafrost are sparsely populated and remote, and contain vast natural resources in timber, minerals, oil and natural gas. Permafrost also contains almost twice as much carbon in the form of frozen organic matter as is in today's atmosphere, frozen and inert for thousands of years. The remoteness, coldness and sheer scale of permafrost give the impression of stability on geologic time scales. But they are also the regions that will be hit first and hardest by the warming effects of climate change, because the Northern Arctic region is warming at twice the global rate. Should the permafrost thaw, the changes would be swift and irreversible, with global social, economic and climatic consequences.

Few people outside the scientific community understand how climate change impacts the people and ecology in permafrost regions, and fewer still realize that thawing permafrost can influence global climate. This report attempts to bridge the gap between the knowledge of science and the needs of policy, informing international leaders, representatives and science experts, who are negotiating a global climate change treaty or defining national policy on the impacts of a changing climate on permafrost and the impact of thawing permafrost on global climate.

The main objective of this report is to make decision-makers and the public aware of the global consequences of thawing permafrost and offer specific and practical policy recommendations. The report does not describe in detail the complete status of our current knowledge of permafrost or the complex processes that drive permafrost dynamics, nor does it identify science research priorities. There are other documents and reports that serve those functions. Instead, it strives to create a simple reference for the policy-maker to understand the basics of permafrost and why these specific recommendations are made. Consequently, the report is short, with graphics and pictures chosen to illustrate the basic processes. The report places the policy recommendations in a scientific, social and economic context by defining basic terminology and describing the fundamental processes that drive permafrost dynamics.

2. An Overview of Permafrost

2.1 What is Permafrost?

Permafrost is perennially frozen ground remaining at or below 0°C for at least two consecutive years (Brown *et al.* 1998). Permafrost regions occupy about 24% of the exposed land area in the Northern Hemisphere (Zhang *et al.* 1999, Figure 1). Permafrost also occurs in high mountainous regions in South America and ice-free regions of Antarctica. Permafrost does not occur everywhere, so permafrost regions are classified into zones based on the fraction of land area that contains permafrost. *Continuous permafrost* zones have permafrost underlying 90-100% of the land area; *discontinuous permafrost* zones have 50-90%; and *sporadic permafrost* 10-50%. *Isolated patches* refer to regions where permafrost underlies less than 10% of the land area.

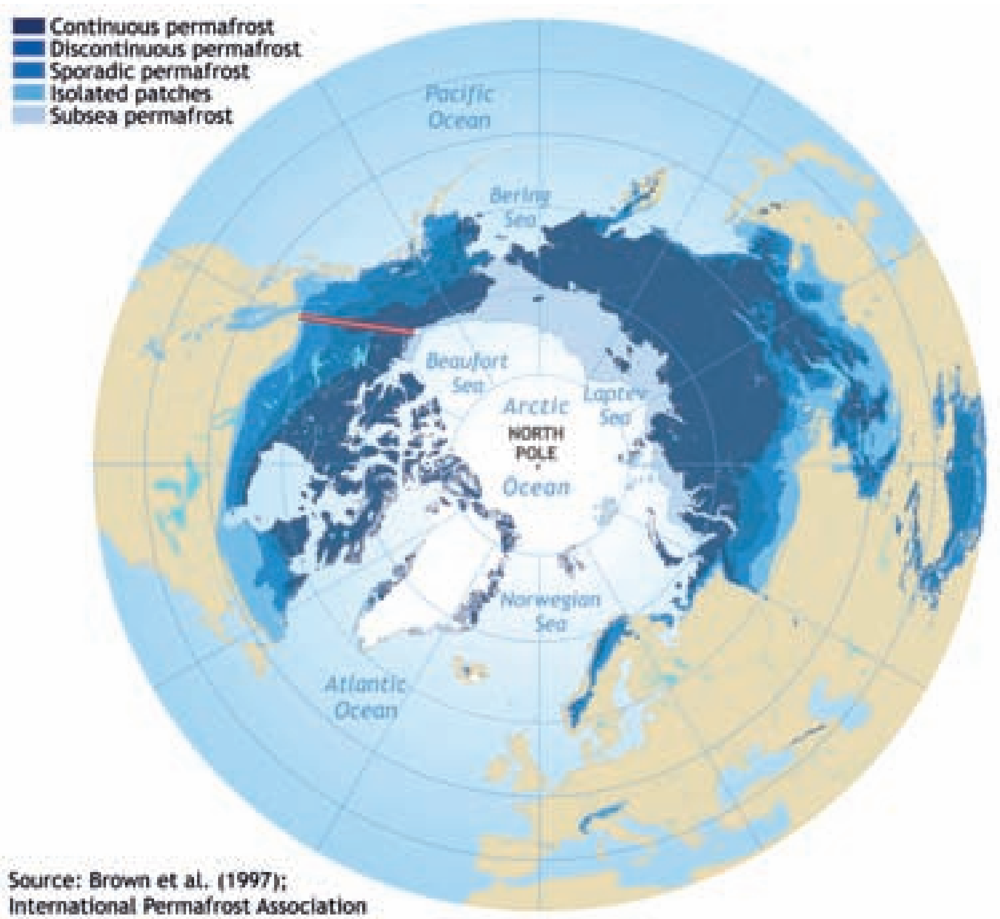


Figure 1: About 24% of the northern hemisphere land surface contains permafrost, divided into continuous, discontinuous, sporadic and isolated zones. The red line shows the location of the permafrost cross section in Figure 4 *(Adapted from Brown et al. 1998).*

The *active layer* is the surface layer of soil that thaws each summer and refreezes each winter (Figure 2). The active layer starts thawing in spring after the snow melts and continues to thaw until fall, reaching a maximum depth in late summer. The active layer begins to refreeze in fall with the onset of winter and is completely frozen by late winter or early spring. Active layer thickness is the annual maximum thaw depth at the end of the summer. *Active layer thickness* ranges from less than 30 cm in continuous permafrost along the Arctic coast, to 2 meters or more in discontinuous permafrost of Southern Siberia, and several meters in the European Alps and on the Qinghai-Tibetan Plateau.

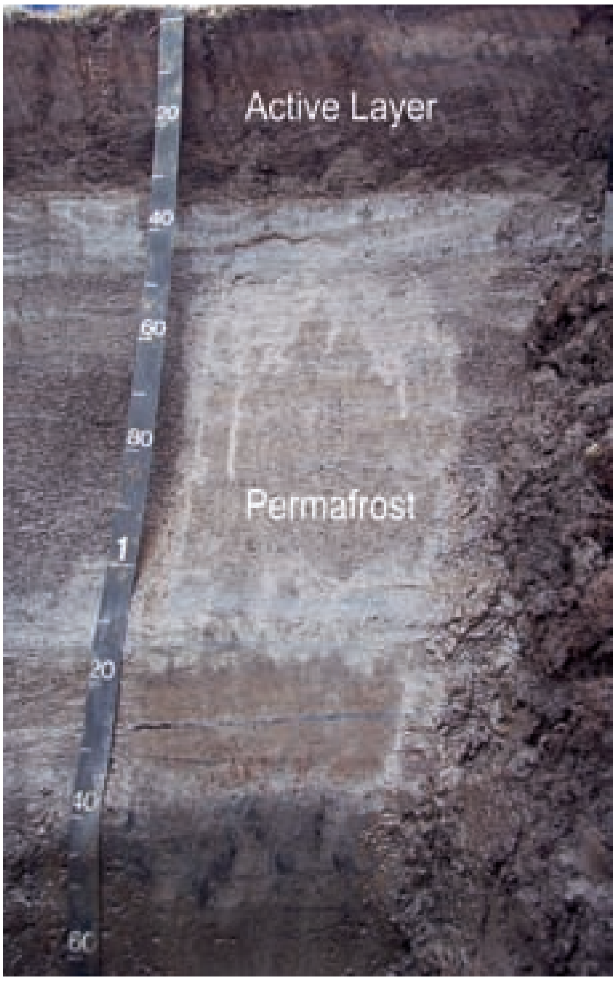


Figure 2: The thickness of the active layer at this site on the North Slope of Alaska is approximately 35 centimeters *(photo: Gary Michaelson).*

The vertical structure of permafrost is determined by the soil temperature (Figure 3). Permafrost is bounded on the top by the *permafrost table* and on the bottom by the permafrost base. The depth to the permafrost base depends on a balance between freezing from the surface and warming from the Earth's interior. Permafrost temperatures at deeper depths reflect variability in climate conditions at longer time scales because heat diffuses slowly through permafrost. Seasonal variability in ground temperature reflects variability in air temperature, but becomes increasingly muted with depth. *The depth of zero annual amplitude* is where the permafrost temperature has no seasonal variation at all. Permafrost temperatures below the depth of zero annual amplitude reflect long-term changes in average climate conditions. The depth of zero annual amplitude varies from a few meters in discontinuous permafrost to 20 meters or more in continuous permafrost or in bedrock (Smith *et al.* 2010; Romanovsky *et al.* 2010a). Temperatures at the depth of zero annual amplitude reflect climate conditions at the end of the 20th century, but temperatures at 400 to 800 meters depth reflect the climatic conditions at the Holocene optimum around 8,000 years ago, just after the end of the last ice age (Osterkamp and Romanovsky 1999; Haeberli 2000).

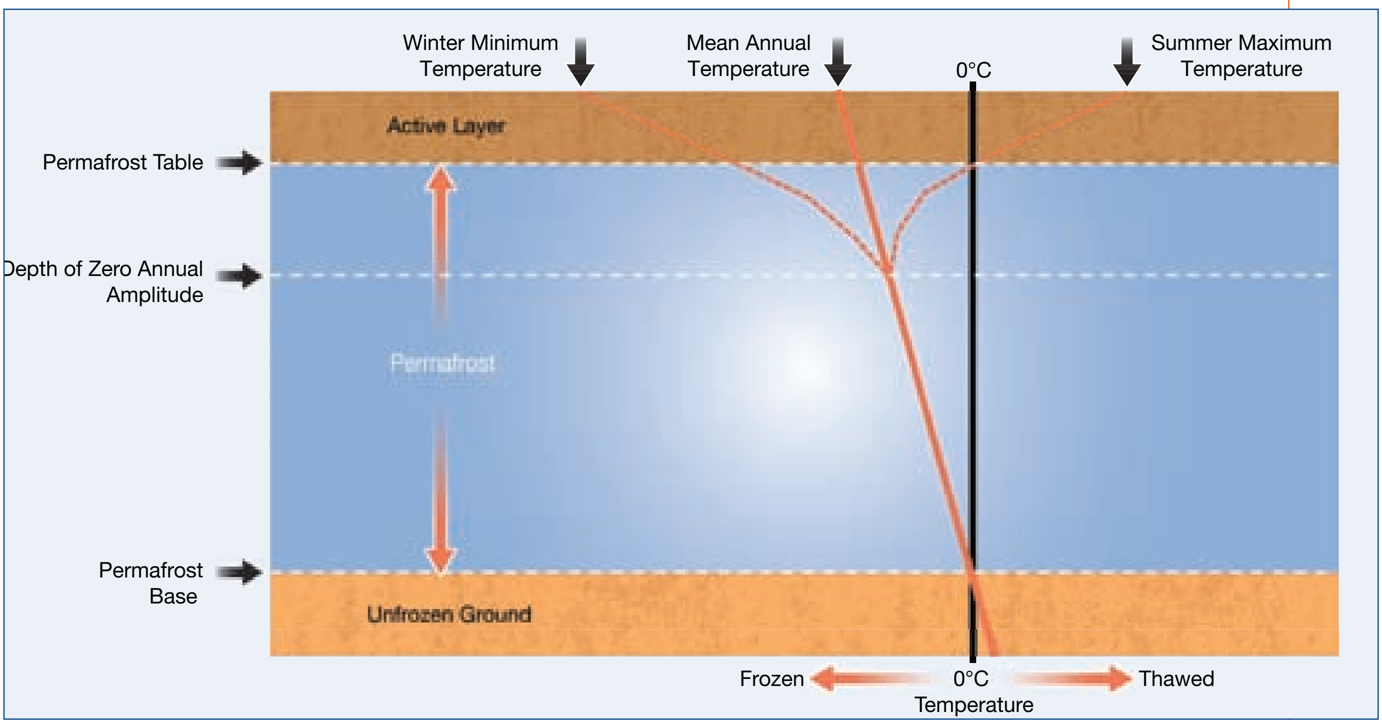


Figure 3: The vertical structure of permafrost is defined by temperature. The active layer is the surface soil that thaws each summer and refreezes each winter. The top of the permafrost layer is the permafrost table and the bottom is the permafrost base.

A *talik* is a layer or body of permanently unfrozen ground in a region of permafrost (French 2008). A *closed talik* is below the active layer, but above the permafrost table. Closed taliks that form under lakes and rivers where the water does not completely freeze in winter are often called thaw bulbs. An *open talik* (sometimes called a *through talik*) extends all the way down to the permafrost base, effectively connecting the surface soil to the unfrozen ground beneath the permafrost. Taliks occur in all permafrost regions, but tend to occur more frequently in discontinuous permafrost.

Permafrost is deep and continuous in the North where temperatures are lowest, transitioning to discontinuous and finally sporadic patches of permafrost further south where temperatures are higher (Figure 4). The coldest and deepest permafrost occurs where air temperatures are lowest: near the Arctic coast in Siberia, the Canadian Archipelago and the ice-free areas of Antarctica (Smith *et al.* 2010, Vieira *et al.* 2010). Generally, continuous permafrost is cold and deep while discontinuous permafrost is relatively warm and shallow (Christiansen *et al.* 2010; Romanovsky *et al.* 2010a, b; Smith *et al.* 2010). Regions with the coldest winters develop the deepest permafrost, ranging from 400 to 600 meters in northern Alaska and northern Canada to 1500 meters in northern Siberia.

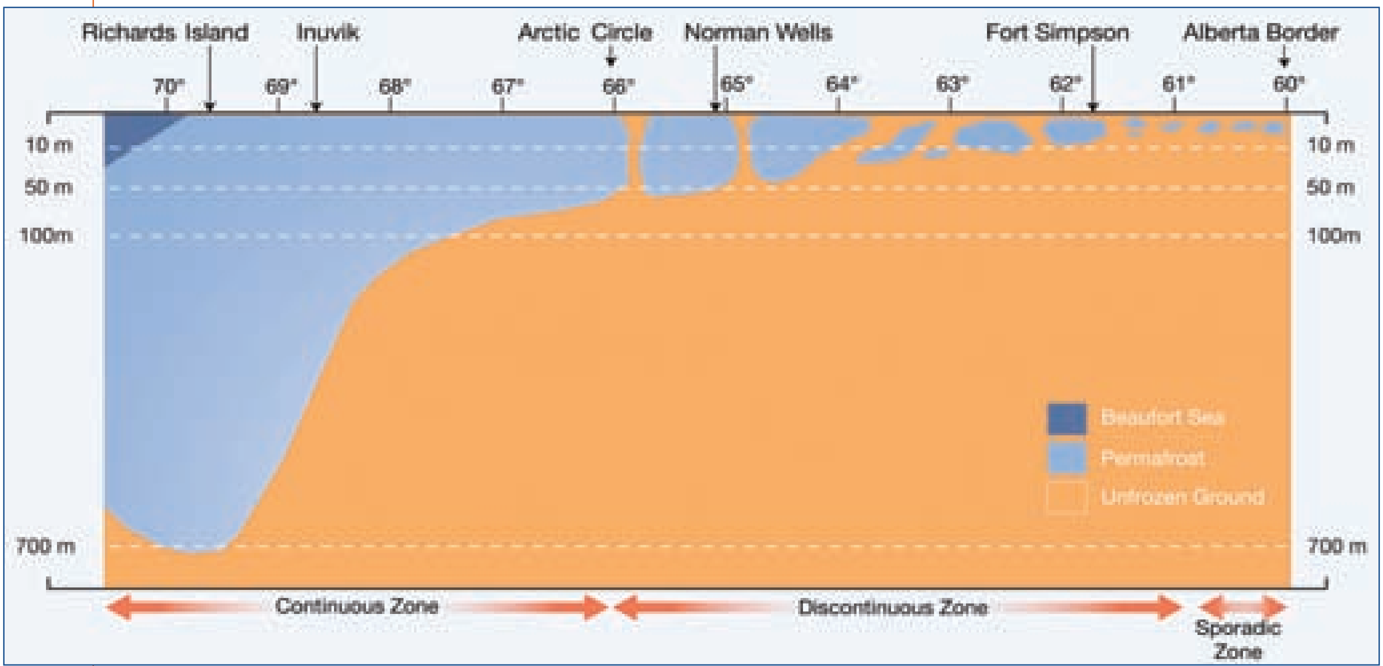


Figure 4: This north-south cross section shows permafrost as a function of latitude and depth along the Mackenzie River basin in Canada (red line in Figure 1). The permafrost changes from deep, cold, continuous permafrost along the Arctic coastline to shallow, warm sporadic permafrost in Alberta *(adapted from Brown et al. 1998).*

Mean air temperature also decreases with altitude, resulting in permafrost formation in mountainous regions at lower latitudes. Permafrost is found in the Rocky Mountains in North America, the European Alps, the Qinghai-Tibetan Plateau in Asia and the Andes in South America. The fraction of land area containing permafrost increases with altitude, so the distribution of permafrost is *sporadic* at low altitudes, transitioning to *discontinuous* and finally *continuous* permafrost at the highest altitudes (French 2002). The permafrost line is the lowest altitude where permafrost can exist and, like the snow line, the permafrost line increases in altitude towards the equator where temperatures are higher (French 2002).

Most of the current permafrost formed during or since the last ice age over the last 100 thousand years. Some relatively shallow permafrost on land typically extending only to depths of 30 to 70 meters formed during the last 6,000 years. Very shallow permafrost with depths from a few to 20 meters formed during the Little Ice Age in the 16th and 19th centuries along the southern permafrost boundary in sporadic and discontinuous permafrost zones. Sub-sea permafrost in the East Siberian Sea and elsewhere along the Arctic coastline was formed when these regions were above sea level, but were inundated after the last ice age ended more than 15,000 years ago.

Permafrost includes the contents of the ground before it was frozen, such as bedrock, gravel, rocks, silt and organic material. Ice acts like cement to bind soil and rock together such that permafrost is hard, durable and resistant to erosion. Plant roots cannot penetrate permafrost, so live vegetation is restricted to the active layer. Annual refreezing slows the decay of plant and animal remains, often resulting in accumulation of organic matter in the active layer and upper permafrost. Soil water expands by 9% when it freezes such that the ground surface rises by 1 to 3 cm in the winter when the active layer freezes, then subsides in the summer when it thaws (Walker *et al.* 2008; Liu *et al.* 2012). Soil expansion and contraction associated with repeated freezing and thawing over decades and centuries provides a mechanical force that tends to redistribute the contents of the active layer, often creating surface features like rock circles unique to permafrost regions.

Permafrost often contains bodies of ice in the form of lenses, layers and wedges collectively referred to as *ground ice*. After the active layer has completely frozen in winter, extreme cold conditions can cause the soil to contract and crack. Water flowing into these cracks in spring will freeze and expand, creating a vertical *ice wedge*. Wedges intersect to form polygons (Figure 5) and only form under extreme cold winter conditions in continuous permafrost (French 2008). Horizontal *ice lenses* and *layers* form as the active layer freezes in the fall and winter when fine-grained soil material like silt and clay draw liquid water toward ice through surface tension and capillary suction. Ice lenses and layers are seen in all permafrost regions, but predominantly form in fine-grained silt or clay soils (French 2008). Over decades and centuries these lenses, layers and wedges can grow to thicknesses often exceeding 1-2 meters. At some locations, ground ice may occupy up to 80% of the soil volume in the upper 20 to 30 meters of permafrost (Kanevskiy *et al.* 2011).

Figure 5: This image of the Lena river delta in Siberia shows polygons formed by the intersection of ice wedges *(photo Konstanze Piel / Alfred Wegener Institute)*

Permafrost degradation is any increase in active layer thickness or permafrost temperature, the formation of taliks, or a decrease in the areal extent of permafrost over time. Permafrost degradation is driven by increases in air temperature and snow depth, as well as disturbances such as fire. The resilience and vulnerability of permafrost to climate change depends on complex interactions among topography, water, soil, vegetation and snow (Jorgensen *et al.* 2010).

Permafrost degradation is often accompanied by erosion and other physical changes to the landscape. Permafrost is highly erosion resistant, but if it warms and thaws, the ice which "glues" the soil together softens and drains away, making thawing permafrost extremely vulnerable to erosion or sudden collapse (Kääb *et al.* 2007). When ice wedges and lenses melt and drain away, the overlying soil can collapse, creating a *thermokarst* depression (Figure 6). If the depression has no outlet, it can fill with water to form a *thermokarst lake*. A talik or thaw bulb under the thermokarst lake can substantially accelerate thaw of surrounding permafrost (Jones *et al.*, 2011). The bonding strength of ice disappears when permafrost thaws, making it vulnerable to *thermal erosion*. Any surface disturbance can start permafrost degradation and trigger thermokarst or thermal erosion, both natural disturbances, such as tundra or forest fires, and anthropogenic disturbances, such as road building or agricultural activities (Grosse *et al.* 2011).

Figure 6: A typical thermokarst depression forms when melting ground ice causes the overlying vegetation and soil to collapse. This thermokarst depression formed when an ice layer about one meter thick melted in continuous permafrost on the North Slope of Alaska *(Photo: Kevin Schaefer).*

2.2 What Controls Permafrost?

Air temperature is the dominant control on global permafrost distribution, followed by local snow characteristics and other environmental conditions. Any location with annual average air temperatures below freezing can form permafrost (Humlum 1998b; Stocker-Mittaz *et al.* 2002). However, depending on the amount of snow and other environmental conditions, permafrost may be present in regions with mean annual air temperature as high as 2°C or absent where annual average air temperature is as low as -20°C (Jorgensen *et al.*, 2010). The major component of snow is air, making it a very effective insulator, often resulting in ground temperatures 5 to 20°C higher than winter air temperatures and permafrost temperatures 3 to 6°C higher than the mean annual air temperature (Harris 2001; Luetschg *et al.* 2004; Zhang, 2005; Jorgensen *et al.*, 2010). Snow thickness, timing and duration influence ground temperature (Zhang 2005). A cold location with deep snow may not form permafrost, while a warmer location with no snow could form permafrost. Sunlight, surface vegetation and soil organic matter can also influence permafrost formation and active layer thickness. In mountains, for example, permafrost will form in shaded depressions, but not on sunlit ridges (Haeberli *et al.* 2012). The distribution of permafrost in mountain areas depends on slope, orientation to the sun, vegetation and snow characteristics. For example, a north-facing, shaded slope may develop permafrost, while a nearby south-facing, sunlit slope may not.

The primary control on active layer thickness (ALT) is the summer air temperature, as well as soil moisture and thermal properties (Romanovsky and Osterkamp, 1997; Shiklomanov *et al.* 2010). Higher summer air temperatures result in deeper active layers, while wetter soil results in shallower active layers. The effects of surface vegetation and organic soil matter often result in large variability in active layer thickness within the space of a few meters (Humlum 1998a). Shading by vegetation reduces the sunlight absorbed by the soil, resulting in shallower active layers than bare exposed soil. The presence of organic matter in the soil tends to result in shallower active layers. In discontinuous permafrost, shading by surface vegetation and the insulating effect of thick organic soil or peat is often required for permafrost to exist at all (Shur and Jorgensen, 2007).

2.3 Permafrost Monitoring

The primary measurements to monitor the status of permafrost are permafrost temperature and active layer thickness. Other observations include sample drilling, remote sensing to detect changes in land surface characteristics and measurements of surface subsidence or heave. There are two global networks to monitor permafrost: the Thermal State of Permafrost (TSP) network, which coordinates measurements of permafrost temperature; and the Circumpolar Active Layer Monitoring (CALM) network, which coordinates measurements of active layer thickness (Figure 7).

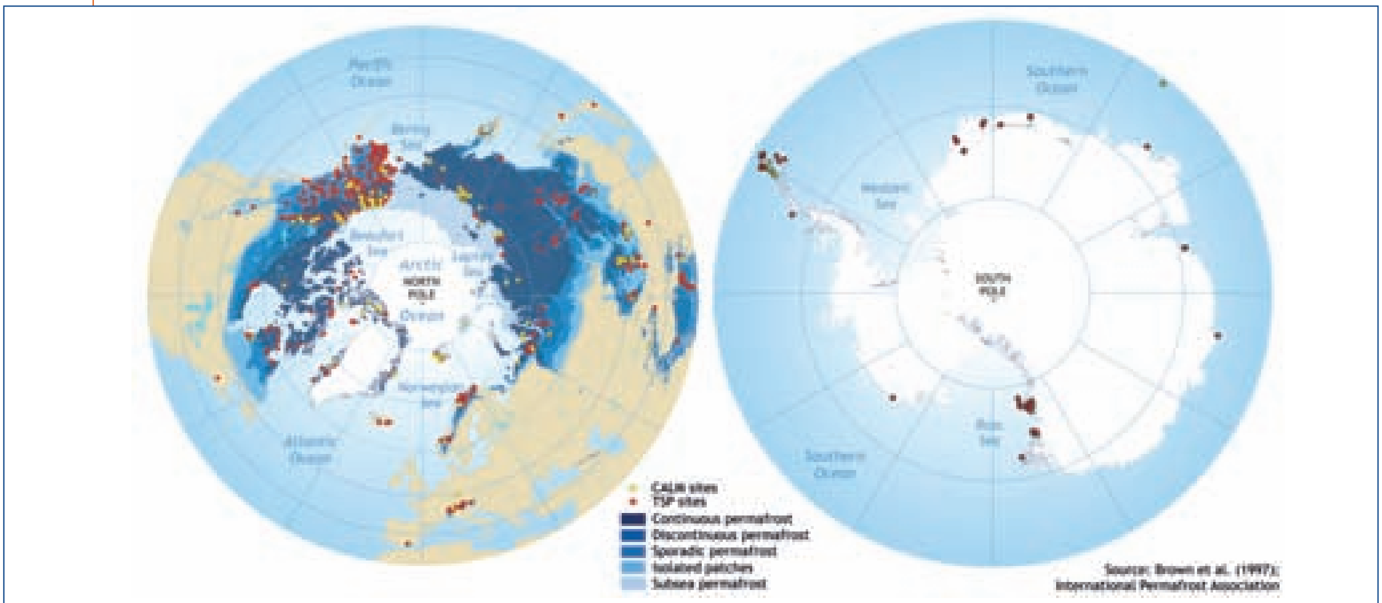


Figure 7: The Circumpolar Active Layer Monitoring (CALM) network measures active layer thickness and the Thermal State of Permafrost (TSP) network measures permafrost temperature.

The TSP and CALM networks are the two components of the Global Terrestrial Network for Permafrost (GTN-P). The GTN-P was initiated by the International Permafrost Association (IPA) to organize and manage a global network of permafrost observations for detecting, monitoring and predicting climate change, and is authorized under the Global Climate Observing System (GCOS) and its associated organizations. GCOS and the Global Terrestrial Observing System (GTOS) jointly identified permafrost temperature and active layer depth as essential climate variables for monitoring the state of the cryosphere and global climate. The IPA developed the implementation strategy for GTN-P, which GCOS approved in 1999. The IPA currently coordinates international development and operation of the TSP and CALM networks for the GTN-P.

The TSP network measures permafrost temperature at multiple depths using boreholes. Boreholes vary in depth from a few meters to a hundred meters and deeper, with a string of temperature sensors at multiple depths. Newer boreholes are automated, but manually lowering a single sensor probe down a borehole to measure temperature is still common, especially for boreholes deeper than 40 meters. The oldest boreholes have operated since the middle of the 20th century, with several decades of permafrost temperature observations. The TSP network includes 860 boreholes mostly located in the Arctic, but including boreholes in the European Alps, Antarctica and the Qinghai-Tibetan Plateau (Brown *et al.* 2010, Romanovsky *et al.*, 2010a).

The CALM network measures active layer thickness or maximum annual thaw either mechanically using a probe, or electronically with a vertical array of temperature sensors. The probe is a metal rod sunk into the ground until it hits the hard permafrost table. The active layer depth is measured on the rod and recorded. To account for high spatial variability, workers generally probe the active layer on a specified 1 km or 100 meter grid. Active layer thickness can also be measured by interpolating the depth corresponding to 0°C using temperature sensors placed above and below the permafrost table. The CALM network includes 260 sites, 168 of which have been measuring active layer thickness since the 1990s (Brown *et al.* 2000; Streletskiy *et al.* 2008; Shiklomanov *et al.* 2010).

The TSP and CALM networks need to be standardized and expanded to better monitor permafrost status and provide more timely information to policy-makers. Most stations in TSP and CALM are funded and operated by independent research teams. Funding is limited and irregular, making it difficult to standardize network measurements, support databases of observations and expand the coverage. For example, air temperature and snow depth, both key parameters for understanding changes in permafrost, are not measured at all TSP and CALM sites. TSP and CALM coverage is limited because installation and maintenance costs restrict sites to regions with reasonable access by truck, plane or boat, resulting in a distinct clustering of sites along roads and the Arctic coastline. The research teams in the GTN-P have made tremendous progress, but evaluation of overall permafrost status in a region or country is still very difficult because of the non-standard observations and limited coverage of the TSP and CALM networks. The ability of the GTN-P to provide timely and comprehensive evaluations of the global status of permafrost would benefit greatly from expansion of the TSP and CALM networks, standardizing the measurements and establishing easily accessible databases of observations.

2.4 Current State of Permafrost

Recent warming in the Arctic and mountainous regions has resulted in warmer permafrost and deeper active layers (Christiansen *et al.* 2010; Romanovsky *et al.* 2010b; Smith *et al.* 2010). During the last several decades, permafrost is warming in most regions with evidence of talik formation at some locations in discontinuous permafrost regions. Increased snow cover and warming permafrost resulted in massive development of new taliks in the northwest of Russia, shifting the boundary between continuous and discontinuous permafrost northward in northern Russia by several tens of kilometers (Oberman 2008; Oberman and Shesler 2009; Romanovsky *et al.* 2010b). Measurements of active layer thickness are not conclusive, with some sites showing a clear increase, while others show no increase (Voigt *et al.* 2010; Romanovsky *et al.* 2011).

Permafrost temperatures have risen over the last several decades in Alaska (Figure 8)). Coastal sites show continuous warming since the 1980s and this warming trend has propagated south towards the Brooks Range, with noticeable warming in the upper 20 m of permafrost since 2008 (Romanovsky *et al.* 2011). Permafrost in the Alaskan interior warmed in the 1980s and 1990s, but has generally stabilized during the last ten years (Osterkamp 2008). Northern Russia and northwest Canada show increases in permafrost temperature similar in magnitude to those in Alaska during the last 30 to 35 years (Drozdov *et al.* 2008; Oberman 2008; Romanovsky *et al.* 2010b; Smith *et al.* 2010). Air temperatures above the Arctic Circle are increasing at roughly twice the global average (Figure 10, below), so the same pattern repeats across the Arctic with coastal sites warming faster than more southerly sites (Romanovsky *et al.* 2010a).

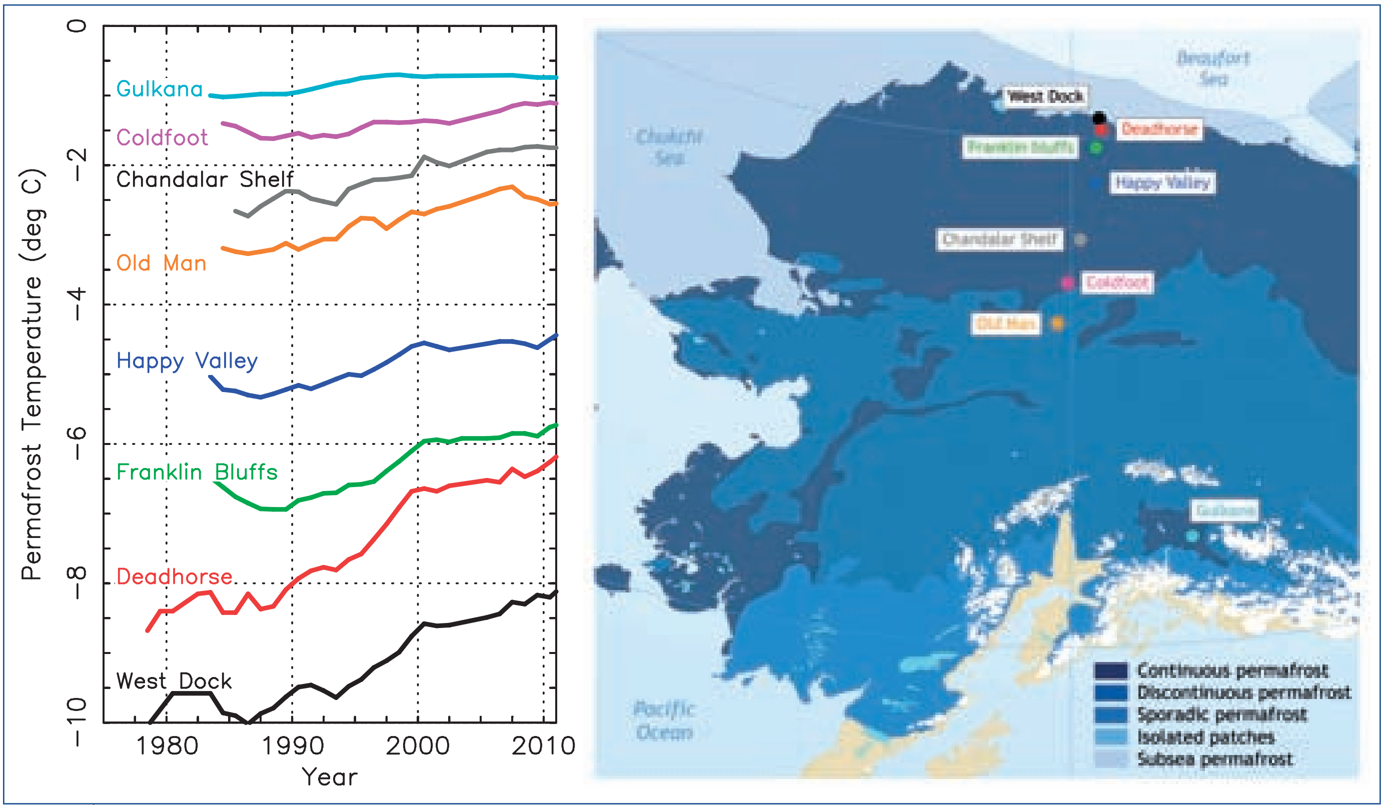


Figure 8: Permafrost temperatures at 20 meters depth have risen over the past 30 years, as seen in these temperature observations from a north-south transect of TSP sites in Alaska *(modified from Romanovsky et al. 2011).*

Trends in active layer thickness are less conclusive, with some sites showing increases, but others showing no trend at all. Active layer thickness has increased in the Russian European North, but not in West Siberia (Mazhitova 2008; Vasiliev *et al.* 2008). Increases in summer air temperature have increased the active layer thickness on the Qinghai-Tibet Plateau (Wu and Zhang 2010; Zhao *et al.* 2010). Although active layer thickness has increased in the Alaskan and Canadian interior, there is no obvious trend near the Arctic coastline (Streletskiy *et al.* 2008; Shiklomanov *et al.* 2010; Smith *et al.* 2009; Burn and Kokelj, 2009; Smith *et al.* 2010).

Melting of excess ground ice might explain the lack of consistent trends in active layer thickness even though permafrost temperatures show clear signs of warming. Year-to-year variability in active layer thickness due to variations in summer air temperature also makes it difficult to detect long-term trends (Smith *et al.* 2009; Popova and Shmakin 2009). However, radar measurements near Prudhoe Bay indicate the surface has subsided by several centimeters since 1992, even though nearby CALM sites showed no obvious increases in active layer thickness (Liu *et al.* 2010, 2012). The excess ground ice in near-surface permafrost, if present, melts slowly over several years, the water drains away and the ground surface settles, a process that is difficult to detect using mechanical probing at CALM sites.

3. Impacts of Climate Change on Permafrost

3.1. Future Climate

The increase over time in global average surface air temperature depends on the total amount of anthropogenic greenhouse gas emissions (Figure 9). To compare projections of future climate from various models in their Fourth Assessment Report, the IPCC defined standard scenarios of potential future anthropogenic greenhouse gas emissions based on different assumptions of economic activity, population growth and fossil fuel use (IPCC 2007). Anthropogenic greenhouse gases include CO_2 and methane, as well as other trace gases such as nitrous oxide and chloroflorocarbons. The scenarios in Figure 9 represent aggressive reductions in emissions (B1), moderate reductions (A1B), and no emission reductions or 'business as usual' (A2). Since publication of the Fourth Assessment Report in 2007, actual emissions have exceeded the A2 emissions. The multi-model ensemble means in Figure 9 represent the scientific community's best estimates of future warming due to anthropogenic greenhouse gas emissions.

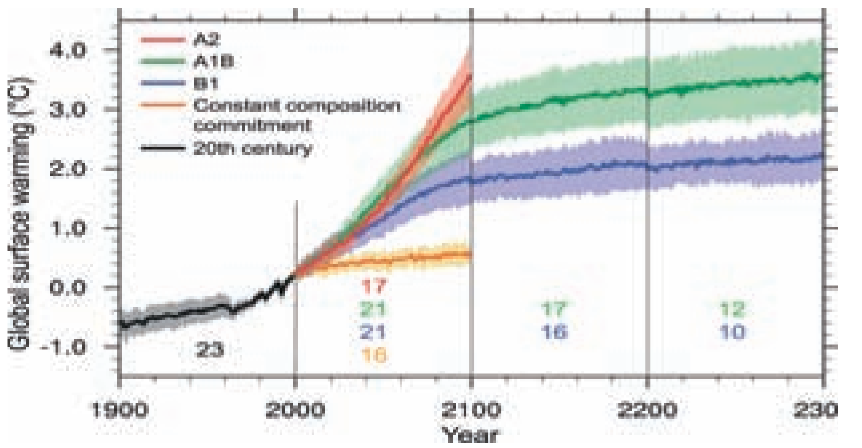
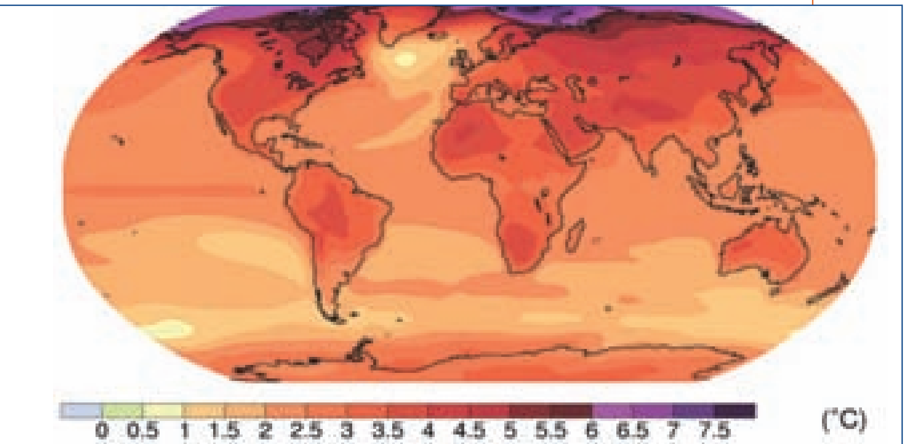


Figure 9: Projections of global average potential surface warming for three different possible scenarios of future anthropogenic greenhouse gas emissions (A2, A1B and B1) plus the warming the world is committed to even if all emissions stopped in 2000 . The colored lines represent the ensemble mean of multiple models and the shading denotes the ±1 standard deviation between models. The colored numbers are the number of models used to calculate the mean and standard deviation *(IPCC 2007, Figure 10.4).*

In the Arctic, the increases in the average surface air temperature will be nearly double the global average (IPCC 2007). Figure 10 shows surface warming based on the moderate, A1B scenario of future anthropogenic greenhouse gas emissions (IPCC 2007). Global warming due to anthropogenic greenhouse gas emissions is amplified in the Arctic due to reduced snow and ice cover (Serreze *et al.* 2011). As temperatures rise, the highly reflective sea ice and snow start to melt, increasing the amount of sunlight absorbed by the Earth's surface, which in turn causes further warming and melting.

Precipitation is expected to increase by 30% in the Arctic based on the moderate, A1B scenario (Figure 11) (IPCC 2007). Model projections indicate precipitation increases in the Arctic and decreases in warmer, temperate latitudes. Precipitation will increase in the Arctic because warmer air holds more water, so air masses transported over land during storms will carry more water. As these warm moist air masses clash with cold air from the Arctic, they will shed their moisture, resulting in increased precipitation. A similar effect occurs in mountainous regions, where precipitation is also expected to increase during winter.

Figure 10: By 2099, the increases in average surface air temperature in the Arctic are expected to range between 5 and 6°C, nearly double the global average of 3°C based on this multi-model mean from the IPCC Fourth Assessment Report. The units are degrees centigrade and the changes are annual means for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999 *(IPCC 2007, Figure 10.8).*



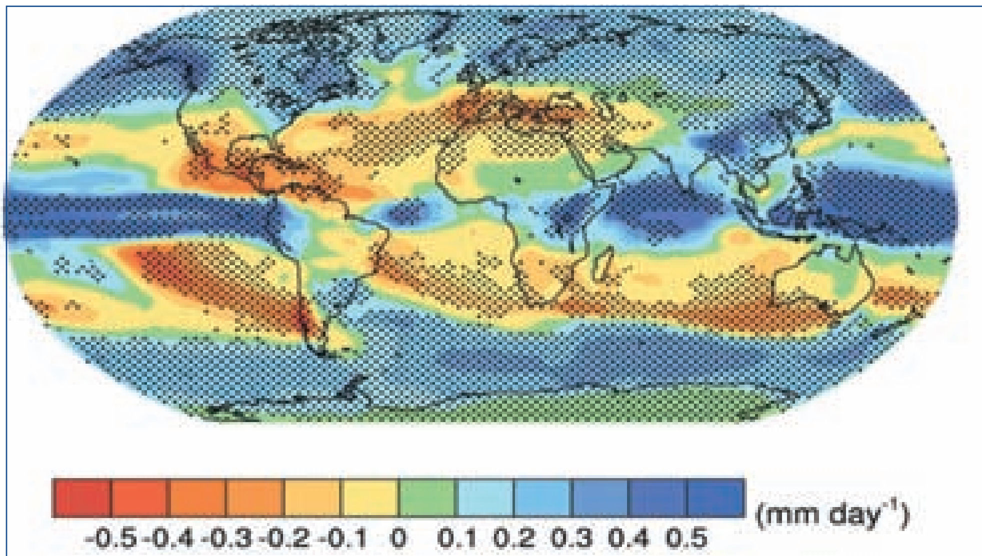


Figure 11: By 2099, precipitation is expected to increase in the Arctic and decrease in temperate zones based on this multi-model mean from the IPCC Fourth Assessment Report. The units are millimeters per day and the changes are annual means for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Stippled areas indicate where at least eight out of ten models agree *(IPCC 2007, Figure 10.12).*

3.2. Permafrost in the Future

Projections of future permafrost degradation indicate that active layer thickness will increase and the areal extent of near-surface permafrost will decrease (Table 1). Table 1 shows projected decreases in the areal extent of near-surface permafrost and the increases in active layer thickness for areas that retain permafrost for the A1B emissions scenario. The large spread represents uncertainty in projected permafrost degradation resulting from how models represent soil and snow processes, the assumed future scenarios of anthropogenic greenhouse gas emissions, and how strongly the model simulates warming in response to increased atmospheric CO_2.

Table 1: Projected loss of near-surface permafrost and increases in active layer thickness by 2100

Study	Decrease in Permafrost Area (%)	Increase in Active Layer (cm)
Marchenko et al. [2008]	7[a]	162[b]
Schaefer et al. [2011]	20-39	56-92
Euskirchen et al. [2006]	27[a]	-
Saito et al. [2007]	40-57	50-300
Eliseev et al. [2009]	65-80[a]	100-200
Lawrence and Slater [2010]	73-88	-
Lawrence et al. [2008]	80-85	50-300
Zhang et al. [2008a]	16-20[a]	30-70
Schneider von Deimling et al. [2011]	16-46	-
Zhang et al. [2008]	21-24	30-80
Koven et al. [2011]	30	30-60[a]
Lawrence and Slater [2005]	60-90	50-300

[a] calculated from numbers or tables in text
[b] calculated from estimated trends

Permafrost degradation in response to warming starts with increases in active layer thickness followed by talik formation (Figure 12). As temperatures rise, the simulated depth of the active layer increases. Eventually, the active layer becomes so deep it does not completely refreeze during winter, forming a talik (Schaefer *et al.* 2011). The southern margins of permafrost regions have the warmest permafrost and will see the greatest talik formation (Zhang *et al.* 2008). As taliks expand, the permafrost becomes patchy and eventually disappears, moving the boundaries of both continuous and discontinuous permafrost northward and to higher elevations. Although near-surface permafrost in the top few meters of soil may disappear, deeper permafrost may persist for many years or even centuries. The loss of permafrost will progress northward towards regions with colder permafrost that are most resistant to thaw in Northern Siberia and the islands of Northeast Canada.

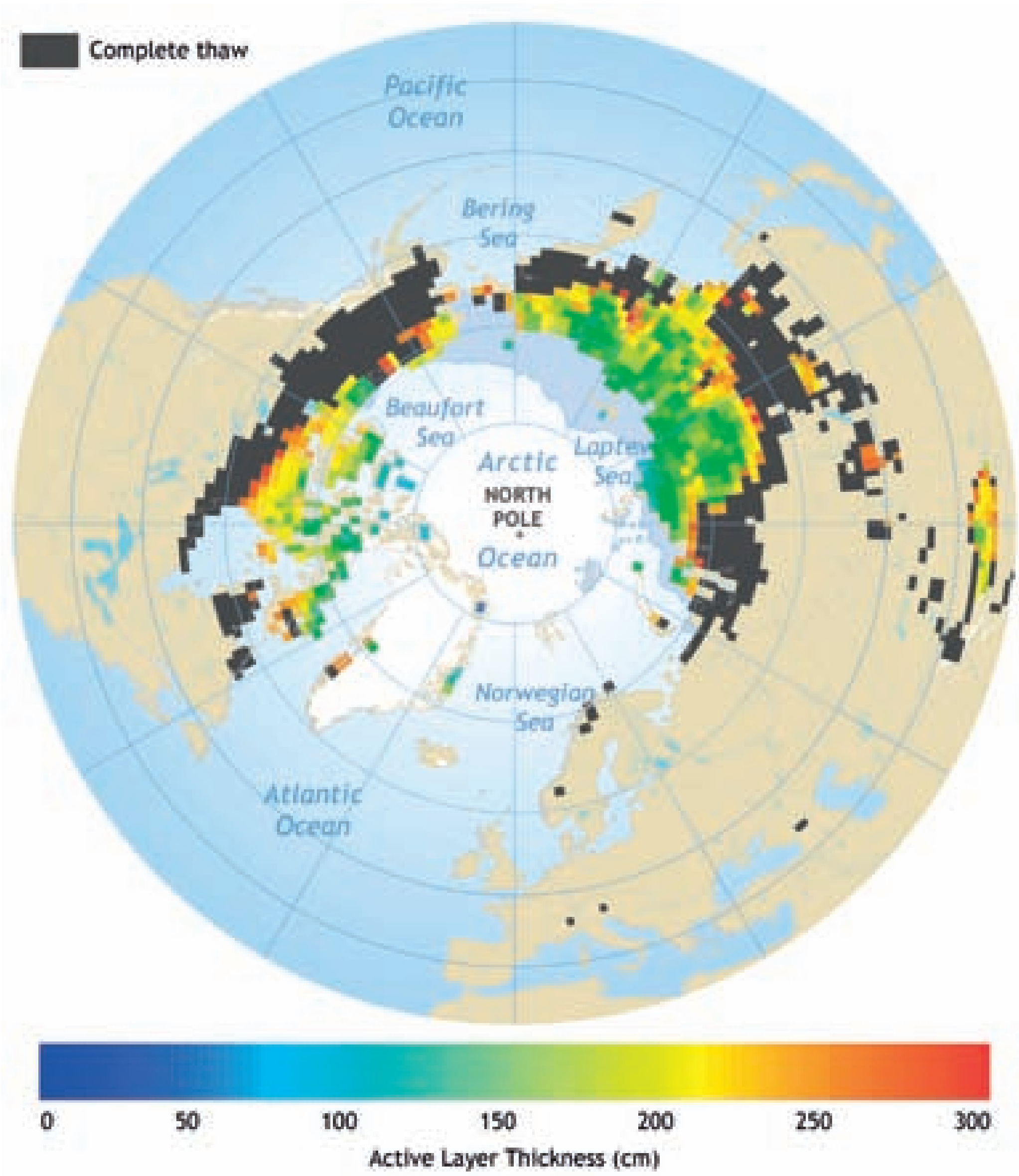


Figure 12: This model projection indicates a 59% loss in near-surface permafrost area by 2100 for the IPCC A1B scenario. The dark grey regions show where taliks may form and permafrost in the top 15 meters of soil may completely thaw *(Schaefer et al. 2011).*

3.3. Erosion

Climate change in the Arctic is expected to increase erosion rates along the Arctic coastline, lake shores and river beds (Figure 13). Coastal erosion has increased during the past few decades because reduced sea ice and rising sea levels have resulted in larger waves during storms in the open water season from June to October (Jones *et al.* 2009; Lantuit and Pollard 2008; Lantuit *et al.* 2011). The average erosion rate along the Arctic coastline is 0.5 meters per year^{-1} (Lantuit *et al.* 2012) with large regional differences. Erosion rates are highest along the Alaskan and Siberian coastlines, which have ice-rich sediment that is more vulnerable to erosion, while river deltas and rocky coastlines in eastern Canada and Greenland are stable or aggrading. Similar processes occur along riverbeds and lake shores throughout permafrost regions (Jones *et al.* 2011).

Figure 13: Warming permafrost softens coastlines, making it more vulnerable to wave action and promoting erosion along the Arctic coast of Alaska. A large block of ice-rich permafrost has detached from the mainland and will quickly disintegrate *(photo: Christopher Arp).*

Thawing permafrost in steep mountain terrain increases the risk of rock falls and landslides (Harris *et al.* 2001). Talus cemented together by ice in mountainous permafrost zones can form *rock glaciers* that creep downhill at velocities of centimeters to several meters per year (Figure 14). If temperatures increase, the ice softens and rock glacier flow velocities increase (Kääb *et al.* 2007; Delaloye *et al.* 2008). If the permafrost thaws, the "cement" holding the talus together drains away, increasing the risk of sudden collapse and landslides (Kääb *et al.* 2007, Roer *et al.* 2008). Rock falls and landslides can trigger additional hazards, such as floods. In 2002, for example, a landslide on Mount Kazbek in Georgia resulting from thawing permafrost dammed the valley below the Kolka glacier, creating a temporary lake that eventually burst (Huggel *et al.* 2005). Landslides due to degrading permafrost frequently block roads over passes in the Andes (Schrott 1998). As mountainous regions warm in the future, the area vulnerable to rock falls and landslides will expand as the permafrost line climbs to higher altitudes (Haeberli and Burn 2002; Haeberli and Hohmann 2008).

Figure 14: Rock and talus debris bonded by ice slowly flow downhill in a typical rock glacier near McCarthy, Alaska *(photo: Isabelle Gärtner-Roer).*

3.4. Ecosystem Disturbances

The dominant ecosystems in permafrost regions are boreal forests to the south and tundra to the north. In mountainous permafrost regions, forests dominate at lower elevations and tundra at higher elevations. Tundra is treeless and typically occurs north of the Arctic Circle or at high elevations. Tundra vegetation is dominated by sedges, shrubs, mosses and lichen. The southern permafrost regions often extend into the boreal forest, which is dominated by evergreen spruce, fir and pine, as well as the deciduous larch or tamarack. The tree line is a narrow transition zone between the tundra and boreal ecosystems. Permafrost is impermeable to water, so rain and melt water pool on the surface, forming innumerable lakes and wetlands throughout permafrost regions. Migratory birds from around the world use these lakes and wetlands as summer breeding grounds.

Permafrost degradation will disturb ecosystems and change species composition, altering wildlife habitat and migration. These disturbances are either slow and continuous or rapid and episodic (Grosse *et al.* 2011). Longer growing seasons due to higher temperatures favor the growth of shrubs and woody vegetation (Figure 15), resulting in a slow and continuous northward migration of the tree line (ACIA 2004). Permafrost degradation also results in more episodic disturbances such as fires, thermal erosion and thermokarst. In some regions, warmer and longer growing seasons result in drier surface soils in late summer, increasing the risk of fire (Grosse *et al.*, 2011). Fire in boreal forests has recently increased in intensity and frequency, and could become more common in tundra regions (Mack *et al.* 2011, Turetsky 2011). These disturbances interact with each other: a fire, for example, might trigger rapid thaw and thermal erosion. Whether slow or rapid, ecosystem disturbances due to permafrost degradation will change species composition, and with it animal habitat and migration.

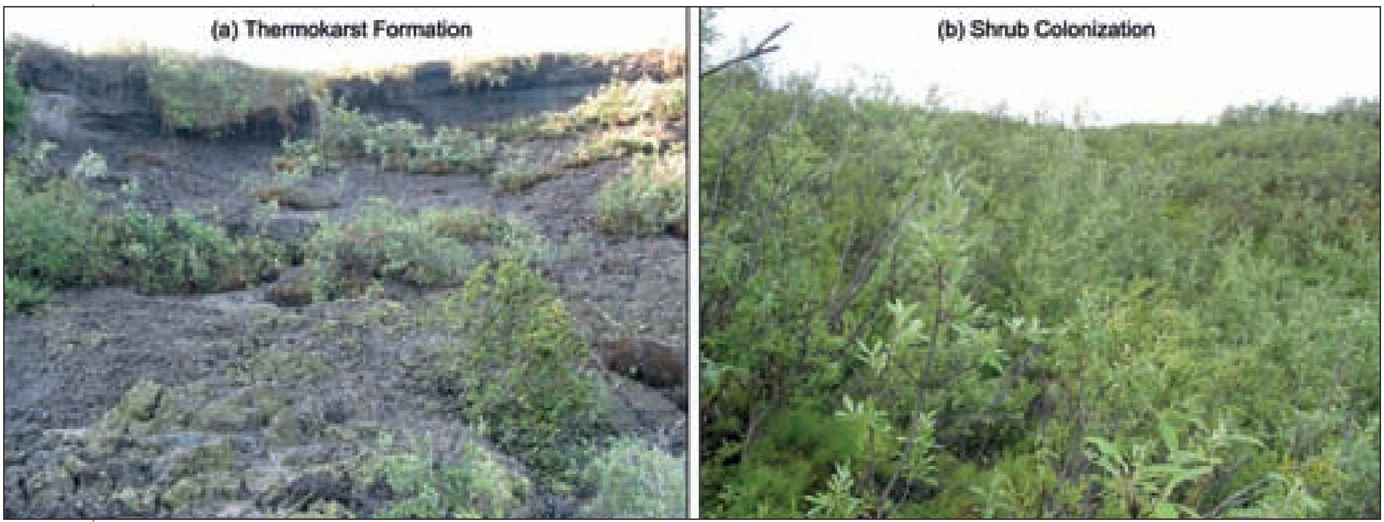


Figure 15: Higher temperatures caused permafrost on this hillside in Alaska to thaw and erode. Deeper active layer depths associated with higher temperatures then favored colonization by woody shrubs *(Photos: Edward Schuur)*.

Ecosystem disturbances due to degrading permafrost will be dominated by changes in local hydrology, with wetlands and lakes forming in continuous permafrost and disappearing in discontinuous permafrost (Smith *et al.*, 2005). In discontinuous permafrost, warming temperatures will expand the thaw bulb under lakes and wetlands. If the thaw bulb reaches the permafrost base, it becomes a through talik, draining the lake down into the groundwater below the permafrost (Figure 16) (Yoshikawa and Hinzman 2003). In continuous permafrost, melting ground ice will form new thermokarst lakes. Over time, these new lakes will also disappear as the continuous permafrost degrades and transitions into discontinuous permafrost. Continuous permafrost will also see a loss of lakes, as melting ice wedges and thermal erosion may breach natural dams and drain existing lakes (Marsh and Neumann 2001). Local topography plays a large role in forming or draining lakes, but the next century will see an overall decline in the number of lakes and wetlands in permafrost regions, with corresponding decline in habitat for waterfowl (Smith *et al.*, 2005).

Figure 16: These shrinking ponds in the Yukon Flats in central Alaska illustrate how lakes in discontinuous permafrost can drain as the thaw bulbs beneath lakes deepen and connect with unfrozen ground beneath the permafrost *(photo: Merritt Turetsky)*.

3.5. Societal and Economic Costs

Thawing permafrost places buildings, roads, pipelines, railways, power lines and similar infrastructure at risk. These structures were built assuming that the solid foundation of permafrost would not change. In fact, local building practices are designed to minimize any potential permafrost degradation. However, thawing permafrost is structurally weak, resulting in foundational settling that can damage or even destroy infrastructure (Figures 17 and 18). Infrastructure failure can have dramatic environmental consequences, as seen in the 1994 breakdown of the pipeline to the Vozei oilfield in Northern Russia, which resulted in a spill of 160,000 tons of oil, the world's largest terrestrial oil spill.

There are only a handful of studies and reports evaluating the economic impacts of permafrost degradation, but these indicate infrastructure maintenance and repair costs will increase in the future. Permafrost degradation will increase future costs to maintain, repair and replace damaged infrastructure. Climate change could add $3.6–$6.1 billion to future costs for public infrastructure in Alaska from now to 2030, an increase of 10% to 20% above normal maintenance costs (Larsen *et al.* 2008). Roughly half the costs fall into the transportation sector (roads and airports) and a third to repair water and sewer systems. This unavoidable cost amounts to about 1.4% of Alaska's annual budget and is comparable to the annual budgets of many state government agencies.

Roads, buildings and other infrastructure in discontinuous permafrost and along the Arctic coast are most vulnerable to damage due to permafrost thaw (Instanes and Anisimov 2008). So far, foundation strength has only slightly decreased due to warming permafrost (Instanes and Anisimov 2008). However, in discontinuous permafrost, where permafrost is relatively warm, small increases in permafrost temperature could substantially reduce foundation strength, placing human infrastructure at high risk. Permafrost along the Arctic coastline often contains salt, such that even a small temperature increase can change ground ice to water, placing infrastructure at high risk (Instanes and Anisimov 2008). Most settlements in permafrost zones are located on the coast, where strong erosion rates place structures and roads at risk and may force the relocation of settlements at considerable cost (Figure 19) (Forbes 2011). This will change local society and culture, as well as upsetting the often fragile balance of small communities and disrupting the traditional interaction of residents and indigenous communities with the permafrost environment (Forbes 2011).

Figure 17: Uneven settling due to permafrost thaw destroyed this apartment building in Cherski, Siberia, which occurred only days after the appearance of the first cracks *(photo: Vladimir Romanovsky)*.

Figure 18: Permafrost thawing near the base of the support pillars caused this bridge on Qinghai-Xizang Highway in Tibet to collapse *(photo: Tingjun Zhang)*.

Figure 19: Coastal erosion of permafrost resulted in the complete destruction of this house in Shishmaref, Alaska.

4. Impacts of Thawing Permafrost on Climate Change

4.1. Frozen Organic Matter

Permafrost soils contain nearly twice as much carbon in the form of frozen organic matter than is currently in the atmosphere (Figure 20). Permafrost soils contain an estimated 1672 gigatonnes (Gt) of carbon (Tarnocai *et al.* 2009). One gigatonne (Gt) of carbon is a trillion kilogrammes of carbon. The current atmospheric CO_2 concentration is ~390 ppm corresponding to ~850 Gt of carbon. Half of the frozen organic matter lies in the top 3 m of permafrost and the rest is in highly localized deposits that can extend down to 30 meters depth. This estimate has a large uncertainty, because it is based on a relatively small number of soil samples extrapolated to the entire permafrost domain (Tarnocai *et al.* 2009). The age of this organic material increases with depth, ranging from 1,000 to 32,000 years, with even older ages in the deepest deposits (Dutta *et al.* 2006; Zimov *et al.* 2006a).

This frozen organic matter was buried during or since the last ice age by slow geological and biological processes that increase soil depth. Dust deposition, sedimentation in flood plains and peat development slowly increased soil depth on time scales of decades to millennia (Schuur *et al.* 2008). Plant remains and organic material at the bottom of the active layer were frozen into the permafrost as the soil deepened over time (Zimov *et al.* 2006a, b). Vertical mixing of the soil during repeated freeze/thaw cycles accelerates the burial process (Schuur *et al.* 2008). The permafrost contains some frozen animal remains from the last ice age, but nearly all the frozen organic matter consists of plant remains (roots, stems and leaves) and partially decayed plant organic material. Decay stops once the soil is frozen, so this organic matter has been preserved, frozen in permafrost, for thousands of years.

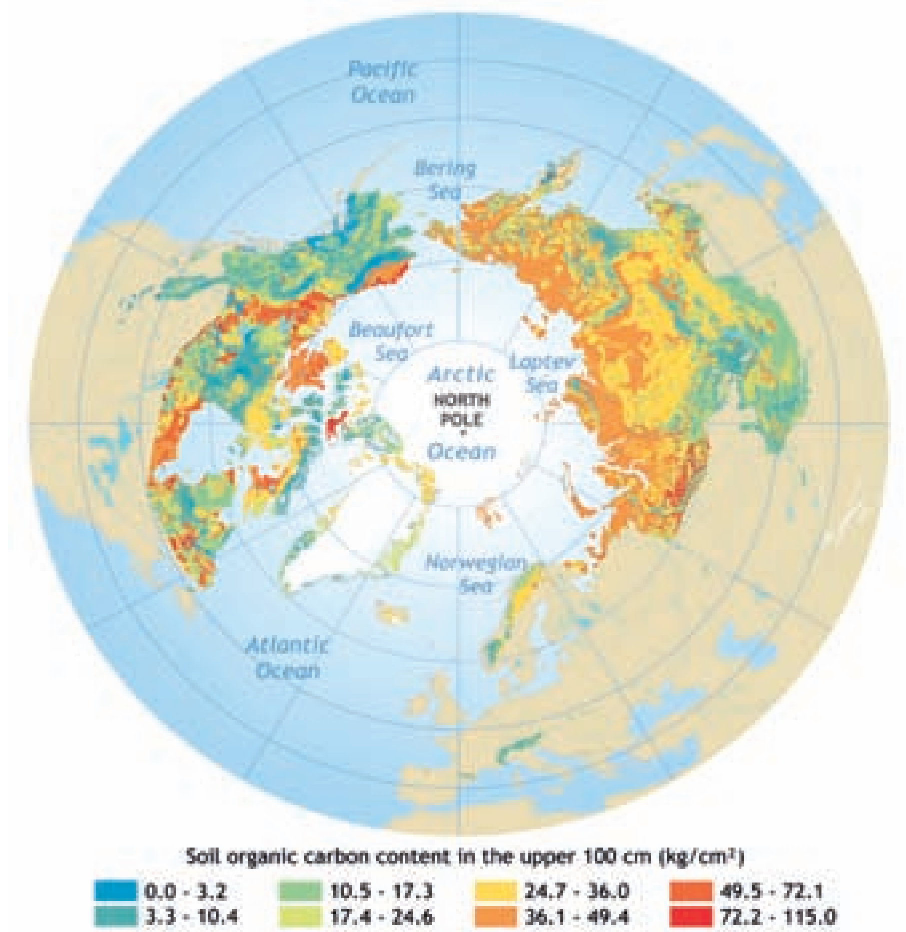


Figure 20: The distribution of frozen organic matter in kilograms of carbon per square meter. Permafrost regions contain about 1700 gigatonnes of carbon in the form of frozen organic matter, nearly twice as much as currently in the atmosphere *(Tarnocai et al. 2009, updated Hugelius et al. 2012).*

4.2. The Permafrost Carbon Feedback

If the permafrost thaws, the organic material will also thaw and begin to decay, releasing CO_2 and methane into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions (Figure 21) (Zimov *et al.* 2006b). Rising air temperatures in the 21st century will thaw some portion of the organic matter currently frozen in the permafrost. Once thawed, microbial decay will resume and convert some of the organic matter into CO_2 and methane. CO_2 and methane are not frozen in the permafrost; rather, the thaw of permafrost triggers decay, which converts the organic material into CO_2 and methane. Thermokarst lakes are especially effective in inducing rapid thaw of permafrost, with subsequent release of substantial amounts of methane (Walter *et al.* 2007). The release of CO_2 and methane from thawing permafrost will amplify the rate of global warming due to anthropogenic greenhouse gas emissions and further accelerate permafrost degradation. This amplification of surface warming due to CO_2 and methane emissions from thawing permafrost is called the *permafrost carbon feedback*.

The permafrost carbon feedback is irreversible on human time scales. With less near-surface permafrost, the burial mechanism described above slows down or stops, so there is no way to convert the atmospheric CO_2 into organic matter and freeze it back into the permafrost. Warmer conditions and increased atmospheric CO_2 will enhance plant growth that will remove CO_2 from the atmosphere (Friedlingstein *et al.* 2006), but this can only to a small degree compensate for the much greater carbon emissions from thawing permafrost. Warmer conditions could promote peat accumulation, as seen after the end of the last ice age, but it is not clear if this would remove enough CO_2 from the atmosphere to compensate for CO_2 released from thawing permafrost.

The effect of the permafrost carbon feedback on climate has not been included in the IPCC Assessment Reports. None of the climate projections in the IPCC Fourth Assessment Report include the permafrost carbon feedback (IPCC 2007). Participating modeling teams have completed their climate projections in support of the Fifth Assessment Report, but these projections do not include the permafrost carbon feedback. Consequently, the IPCC Fifth Assessment Report, due for release in stages between September 2013 and October 2014, will not include the potential effects of the permafrost carbon feedback on global climate.

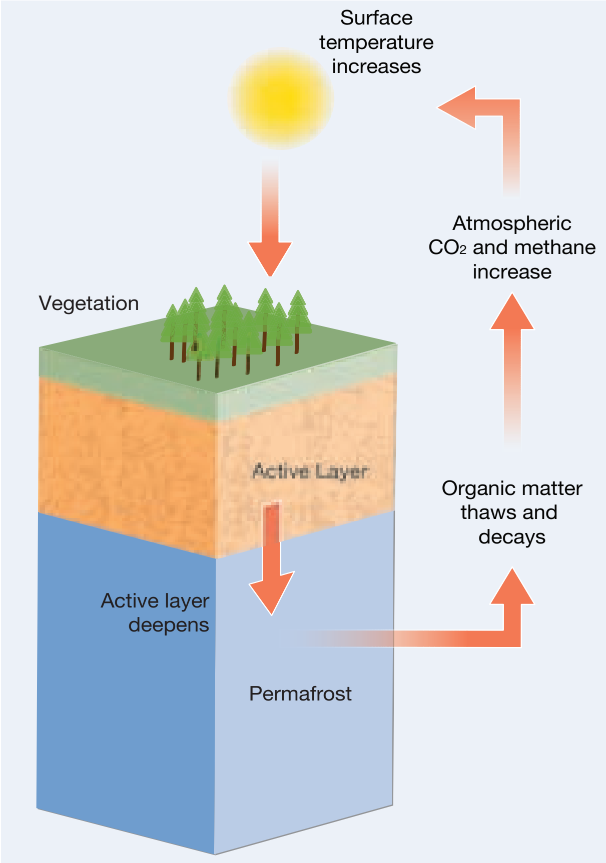


Figure 21: The permafrost carbon feedback is an amplification of surface warming due to the thaw of organic material currently frozen in permafrost, which will then decay and release CO_2 and methane into the atmosphere.

Projections of the strength of the permafrost carbon feedback indicate large potential CO_2 and methane emissions from thawing permafrost over the next 200 years (Table 2). These results indicate a large portion of the frozen organic matter could potentially thaw out and end up in the atmosphere as CO_2 and methane over the next 200 years. A survey of expert opinion produced similar estimates as shown in Table 2 (Schuur *et al.* 2011). Extensive wetlands in the Arctic imply that 2.7% of the emissions from thawing permafrost will be methane (Schuur *et al.* 2011). The IPCC Fourth Assessment report assumes methane is 25 times more potent a greenhouse gas than CO_2 on a century timescale, although accounting for the effect of methane on aerosols indicates this may be closer to 33 times more potent (Shindell *et al.* 2009). Enhanced plant growth currently removes roughly one-quarter of all anthropogenic CO_2 emissions, and projections indicate a cumulative land uptake by 2100 of approximately 160 Gt C (Friedlingstein *et al.* 2006). CO_2 and methane emissions from thawing permafrost could cancel out 15% to 100% of this global land uptake of atmospheric CO_2.

Table 2: Projections of emissions from thawing permafrost, with CO_2 equivalents in parentheses.

Study	Permafrost Carbon Emissions (Gt C)			
	2100	**2200**	**2300**	**Uncertainty**
Schneider von Deimling *et al.* (2012)[a]	26 (43)	320 (415)	529 (686)	33%
Koven *et al.* (2011)[a]	62 (80)	na[c]	na	11%
Schuur *et al.* (2009)[a,b]	85 (110)	na	na	15%
Schaefer *et al.* (2011)[a]	104 (135)	190 (246)	na	34%

[a] CO_2 equivalent calculated assuming 2.7% of total emissions is methane (Schuur *et al.* 2011) and a global warming potential of 33 (Shindell *et al.* 2009)
[b] calculated from emission rates in the paper
[c] not available

There are large sources of uncertainty in these estimates of the permafrost carbon feedback. The exact amount of frozen organic matter is uncertain. Some of the thawed organic matter will be dissolved into the ground water and carried off into lakes and oceans rather than released into the atmosphere as CO_2 and methane, but how much is not known. These estimates do not account for either potential enhanced peat growth, which would compensate for permafrost emissions (Camill *et al.* 2001), or the development of thermokarst features and thermal erosion, which would accelerate permafrost emissions. These estimates all assume different scenarios of future anthropogenic greenhouse gas emissions, and the warming and permafrost thaw in response to a given increase in atmospheric CO_2 varies between models.

The release of CO_2 and methane will persist for a hundred years or more after atmospheric CO_2 stops increasing (Figure 22), influencing the climate system for centuries (Koven *et al.* 2011, Schaefer *et al.* 2011). The decay of thawed organic material is slow because the soil will still be cold and wet (Koven *et al.* 2011, Schaefer *et al.* 2011; Schneider von Deimling, 2012). Also, the thawing of permafrost may persist for decades or even centuries after anthropogenic greenhouse gas emissions have stopped (Schaefer *et al.* 2011).

The permafrost carbon feedback will influence the negotiation of emissions reductions in the international treaty to address global climate change. The treaty currently under negotiation focuses on a target warming of 2°C above pre-industrial temperatures by 2100 (Blok *et al.* 2011). When adopted and ratified, this treaty would succeed the 1997 Kyoto Protocol and place limits on anthropogenic greenhouse gas emissions for each country. The 2°C target is a global average, while warming in the Arctic would be roughly double the global average, or about 4°C. The projections in Table 2 all indicate that emissions from thawing permafrost will irreversibly start sometime in the next few decades, long before reaching the 2°C warming target.

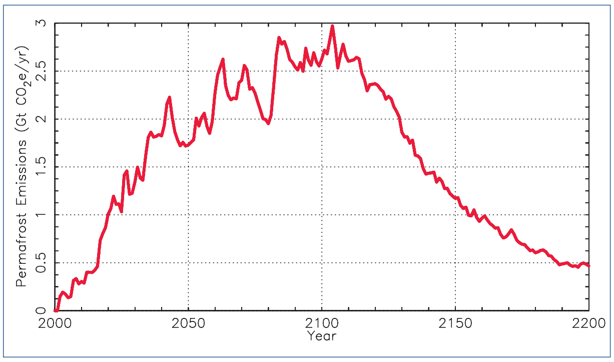


Figure 22: CO_2 and methane emissions from thawing permafrost can continue for decades or even centuries, as seen in this plot of estimated annual permafrost emissions in CO_2 equivalent for the IPCC A1B scenario. In this scenario, anthropogenic emissions stop in 2100, but permafrost CO_2 and methane emissions continue well past 2200 *(Schaefer et al. 2011)*

The calculation of emission reduction targets in the climate change treaty should account for CO_2 and methane emissions from thawing permafrost. The estimates in Table 2 are on a par with the differences in the total allowed greenhouse gas emissions between IPCC scenarios, so the long-term climate after 2100 will be determined by both permafrost and anthropogenic greenhouse gas emissions. A target atmospheric CO_2 concentration of 700 ppm, for example, sets an upper limit on total global carbon emissions of ~1350 Gigatonnes (Schaefer *et al.* 2011). Under this scenario, projections of permafrost emissions in Table 2 would account for 5% to 39% of total emissions, leaving only 61-95% for anthropogenic emissions. Failure to account for CO_2 and methane emissions from thawing permafrost in the treaty may result in overshooting the 2°C warming target.

CO_2 and methane emissions from thawing permafrost will also complicate treaty verification. Verification of emission reductions will involve a combination of emissions reported by individual countries confirmed by estimates of actual emissions derived from models using direct measurements of atmospheric greenhouse gas concentrations. Many countries already have infrastructure to measure atmospheric greenhouse gases and estimate regional emissions, such as the CarbonTracker system in the United States (Peters *et al.* 2005). However, it is not clear whether this infrastructure can detect emissions from thawing permafrost and distinguish them from anthropogenic greenhouse gas emissions.

5. Policy Recommendations

Below are specific policy recommendations to address the potential economic, social and environmental impacts of permafrost degradation in a warming climate. These recommendations attempt to fill gaps in the arsenal of available tools to monitor and respond to permafrost degradation and to raise awareness of issues of global importance to the international policy community. There are many sources of uncertainty in our understanding of permafrost and how it will respond to and influence climate change. However, other reports and plans will address research priorities to reduce uncertainty. These recommendations focus on needs that the scientific community cannot address alone and which require coordinated action by national governments and international organizations.

5.1. Commission a Special Report on Permafrost Emissions

Problem: The greenhouse gas emissions targets currently under negotiation in the international climate change treaty do not account for CO_2 and methane emissions from thawing permafrost. The treaty currently under negotiation to replace the 1997 Kyoto Protocol sets a global target warming of 2°C above pre-industrial temperatures (Blok *et al*. 2011). This 2°C target sets a total limit on global greenhouse gas emissions by 2100. As seen in Table 2, CO_2 and methane emissions from thawing permafrost may be a significant fraction of this total limit. To meet the 2°C warming target, some portion of the total allowed greenhouse gas emissions may have to be set aside to account for CO_2 and methane emissions from thawing permafrost. Not accounting for CO_2 and methane emissions from thawing permafrost could potentially undermine anthropogenic emissions targets currently under negotiation, with the result that the world may substantially overshoot the 2°C warming target.

The climate projections in the IPCC Fifth Assessment Report (AR5) do not include the effects of the permafrost carbon feedback on global climate, limiting its potential to help guide global policy over the next decade. The sections covering permafrost and the global carbon cycle will assess our current knowledge of the permafrost carbon feedback. However, all climate projections in the IPCC's AR5 are likely to be biased on the low side relative to global temperature because none of the participating models include the permafrost carbon feedback. Other key reports, such as *Global Outlook for Ice and Snow* commissioned by UNEP and the *Snow, Water, Ice, Permafrost in the Arctic* assessment commissioned by the Arctic Monitoring and Assessment Programme (AMAP) mention CO_2 and methane emissions from thawing permafrost, but do not quantify how these emissions influence global climate. The IPCC will release the AR5 in stages between September 2013 and October 2014, but to meet deadlines, participating model teams froze new model development in 2009, before the scientific community fully realized the potential effects of the permafrost carbon feedback on global climate. The modeling teams simply did not have time to incorporate the permafrost carbon feedback into their models. None of the global climate projections for the IPCC's AR5 account for the effects of the permafrost carbon feedback, all are biased on the low side relative to global temperature and anthropogenic emissions targets based on these projections would be biased high.

Policy Implication: The IPCC may consider preparing a special assessment report on the permafrost carbon feedback to support climate change policy discussions and treaty negotiations. The report should commission special simulations that evaluate future permafrost degradation, estimate potential CO_2 and methane releases, and identify key unknowns and estimate uncertainty. Most importantly, the report should assess the potential effects of permafrost CO_2 and methane emissions on global climate. A special report on permafrost degradation and how it may influence global climate would complement the AR5, and would provide the international community with the scientific information required to discuss global policy and negotiate anthropogenic emissions targets for the climate change treaty.

5.2. Create National Permafrost Monitoring Networks

Problem: The TSP and CALM networks need to be expanded to adequately monitor permafrost. The TSP and CALM networks are designed for science, not monitoring. Each TSP and CALM site is run by independent research teams with differing research objectives, resulting in different instrument design, installation and operation. Under IPA leadership, participants in TSP and CALM have made tremendous progress, but responding to a simple inquiry about the status of permafrost in a particular country still requires months of detailed analysis and interpretation by dozens of research teams. The TSP network grew during the 2007-2008 International Polar Year (IPY) because of regional efforts funded by national funding agencies. However, funding is still limited and irregular and, as seen in Figure 7, the networks cover only a small part of regions with permafrost. More importantly, comparing the network site map in Figure 7 with the projection of future permafrost degradation in Figure 12 indicates the network sites are not always located where greatest permafrost change and loss are expected.

Policy Implication: Governments may consider creating national permafrost monitoring networks by taking over operation of GTN-P sites (TSP and CALM sites) within their borders, increasing funding, standardizing measurements and expanding coverage into permafrost regions most vulnerable to thaw. This applies to all countries with permafrost, but particularly to those with the most permafrost: Russia, Canada, China and the United States. Switzerland and China successfully created national networks from portions of the TSP, but this is not adequate to monitor permafrost globally. Governments should release annual reports on permafrost status and make the data freely and easily available to all interested parties. The national networks should remain part of the GTN-P under the auspices of the GCOS. The IPA should continue to help steer and coordinate development of the GTN-P.

5.3. Plan for Adaptation

Problem: There are very few studies and reports that quantify the risks, costs and mitigation associated with property and infrastructure damage due to permafrost degradation. As seen above, expensive and extensive damage to buildings, roads and other key infrastructure can occur quickly once permafrost begins to thaw. Governments will have to repair and replace damaged public infrastructure, impacting national and regional budget planning and public services. To plan for the future, government officials need to know the potential social and economic impacts of permafrost degradation.

Policy Implication: Nations with substantial permafrost may consider creating plans evaluating the potential risks, economic costs and potential mitigation strategies associated with permafrost degradation. Again, this applies to all countries with permafrost, but particularly to Russia, Canada, China and the United States. Individual nations may consider identifying regions especially vulnerable to permafrost degradation and within these regions, identifying at-risk structures, infrastructure and industries. Nations may consider engaging economists, engineers and scientists to estimate the repair, replacement and mitigation costs of damaged infrastructure. Engineers and scientists may consider developing new building techniques or adapting current building codes to withstand potential permafrost degradation. Such plans should be developed at the local level, but coordinated nationally and internationally. Adaptation plans will help policy-makers, national planners and scientists quantify costs and risks associated with permafrost degradation.

6. Conclusions

Permafrost around the world has begun to change, with TSP network observations indicating that permafrost temperatures have risen over the past few decades. CALM network observations are less conclusive, but show increases in active layer thickness at many sites. Overall, these observations indicate that large-scale thawing of permafrost may already have started.

Climate projections indicate substantial permafrost loss and degradation by 2100. Wide-spread permafrost degradation will permanently change local hydrology, increasing the frequency of fire and erosion disturbances. The number of wetlands and lakes will increase in continuous permafrost zones and decrease in discontinuous zones. Overall, the total number of wetlands and lakes will decrease as the continuous permafrost zone shrinks, impacting critical habitat, particularly for migratory birds. Risks associated with rock falls and erosion will increase, particularly in cold mountain areas. Damage to critical infrastructure, such as buildings and roads, will incur significant social and economic costs.

Degrading permafrost can release enough CO_2 and methane to influence global climate, amplifying warming due to anthropogenic greenhouse gas emissions. Permafrost contains approximately 1672 gigatonnes (Gt) of carbon in the form of frozen organic matter. If the permafrost thaws, so will the organic matter, which will then decay, potentially releasing large amounts of CO_2 and methane into the atmosphere. Emissions from thawing permafrost could start within the next few decades and continue for several centuries, influencing both short-term climate (before 2100) and long-term climate (after 2100).

The recommendations in the previous section will ensure that the international community has the tools and knowledge to address the impacts of permafrost degradation in a warming climate. They require coordinated action by national governments and international organizations, but if taken into consideration and ultimately implemented, will help the international community understand and respond to global impacts of warming permafrost.

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9. Glossary

Active layer: the surface soil layer in permafrost regions that thaws each summer and freezes each winter.

Active layer thickness: the annual maximum depth of thaw of the soil in summer.

Closed talik: a talik below the active layer, but above the permafrost table.

Continuous permafrost: regions where permafrost underlies 90-100% of the land area.

Depth of zero annual amplitude: the soil depth where the permafrost temperature has no seasonal variation.

Discontinuous permafrost: regions where permafrost underlies 50-90% of the land area.

Ground ice: bodies of pure ice within permafrost in the form of wedges, lenses, and layers

Ice lens or layer: a horizontal body of ground ice formed when fine grained silt and clay draw liquid water toward ice through surface tension and capillary suction.

Ice wedge: a vertical body of ground ice formed by soil contraction in winter. A vertical crack forms due to contraction in winter. Water flows into the cracks in spring, freezes and expands.

Isolated permafrost patches: regions where permafrost underlies less than 10% of the land area.

Open talik: a talik extending down to the permafrost base. Sometimes called a through talik.

Permafrost: soil or rock remaining at or below 0°C for at least two consecutive years.

Permafrost base: the bottom of the permafrost layer within the soil column.

Permafrost carbon feedback: amplification of surface warming due to the release into the atmosphere of the carbon currently frozen in permafrost

Permafrost degradation: any increase in active layer thickness, melting of ground ice, thinning of permafrost, or decrease in the areal extent of permafrost over time.

Permafrost table: The bottom of the active layer and the top of the permafrost layer in the soil column.

Rock glacier: tongue-shaped bodies of perennially frozen material with interstitial ice and ice lenses that move downslope by creep as a consequence of the ice deformation.

Sporadic permafrost: regions where permafrost underlies 10-50% of the land area.

Talik: a layer or body of permanently unfrozen ground in a region of permafrost.

Thaw bulb: a closed talik under lakes and rivers which do not completely freeze in winter

Thermal erosion: surface erosion triggered by permafrost thaw.

Thermokarst depression: a local subsidence or collapse due to the melting of ground ice.

Thermokarst lake: a thermokarst depression or subsidence that is filled with water.

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The UNEP ''Policy Implications of Warming Permafrost'' report describes the current and potential future status of permafrost and makes policy recommendations to address the impacts of permafrost degradation in a warming climate. Climate projections in the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) do not account for carbon dioxide and methane emissions from thawing permafrost. The report recommends commissioning a special report on permafrost emissions from the IPCC, creating national permafrost monitoring networks and developing national adaptation plans for future permafrost degradation.

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