Policy Implications of Warming Permafrost

Thawing permafrost resulted in this erosion gully called a thermokarst (photo: unknown).

Executive Summary

Permafrost is perennially frozen ground under 25% of the land surface in the northern hemisphere. Permafrost distribution and degradation are controlled by air temperature and to a lesser extent, snow characteristics. The primary measurements for long-term monitoring are the permafrost temperature and the active layer thickness (annual surface thaw depth). Observations indicate permafrost temperature has risen and active layer thickness has increased, although increases in active layer thickness are less conclusive. These observations indicate large-scale thawing of permafrost may have already started.

Arctic and alpine temperatures are expected to increase at twice the global rate and projections of permafrost degradation indicate substantial loss of permafrost by 2100. Widespread permafrost degradation will change species distribution and risks of fire and disease across the Arctic. Permafrost degradation will increase risks associated with rock fall and erosion, particularly in mountainous regions. Damage to infrastructure in the Arctic and mountainous regions, such as buildings and roads, will sustain significant social and economic impacts.

Permafrost contains enough frozen carbon to double the current atmospheric CO_2 concentrations. Carbon emissions from thawing permafrost will amplify warming due to the burning of fossil fuels. Carbon emissions from thawing permafrost are irreversible and large enough to significantly influence global climate. Global strategies to reduce fossil fuel emissions must account for permafrost carbon emissions or risk overshooting the target climate.

The following policy recommendations will minimize the economic, social, and environmental impacts of warming permafrost:

1) **Institutionalize Permafrost Monitoring**: National governments should expanded, institutionalized, and run the current networks to monitor permafrost to ensure sufficient high quality measurements to make informed policy decisions.

2) **Allocate for Permafrost Carbon Emissions**: Global treaties or strategies to reduce fossil fuel emissions should include a 15% annual allocation to account for carbon emissions from thawing permafrost.

3) **Plan for Adaptation**: Nations with substantial permafrost should develop plans to minimize the risks, damage, and costs of permafrost degradation.

4) **Commission Special Report on Permafrost**: The Intergovernmental Panel on Climate Change should commission a special report to assess potential permafrost degradation and how carbon emissions from thawing permafrost would influence global climate.

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 is found beneath 24% of exposed land in the Northern Hemisphere. Permafrost may hold the key to the planet's future because it contains huge stores of carbon that, if thawed and released into the atmosphere, would amplify current global warming and even propel us to a warmer world beyond a threshold of no return.

Precisely for this reason, the objective of this report is to inform a broad audience about permafrost, and communicate to decision-makers and the general public the impacts and implications of changing permafrost in a warming climate. It summarizes the best scientific information available from published literature, emphasizing permafrost in the Northern Hemisphere. The report includes the impacts of changing climate on ecosystems and human infrastructure in the Arctic, as well as the impacts of thawing permafrost on global climate. It has been fully populated with graphics, illustrations, and photos to make the concepts and ideas easily understood and visualized by a non-scientific audience.

While much has been written about permafrost in the last couple of years, most such reports are very technical in nature and target a limited, scientific audience rather than the broader group of decision-makers and the general public. The 2011 *Snow, Water, Ice and Permafrost in the Arctic* assessment report produced by the Arctic Monitoring and Assessment Programme focused on impacts of climate change on the Arctic cryosphere, rather than the other way around, and of course did not include all areas with permafrost, particularly in 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 on this project 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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1. Introduction to Permafrost

1.1. 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 occurs primarily in the Arctic and high altitude alpine regions, lying beneath approximately 25% of the land area in the Northern Hemisphere (Figure 1). Permafrost is often not continuous across the landscape: a north-facing, shaded slope may develop permafrost, while a nearby south-facing, sunlit slope may not. Permafrost regions are classified by the fraction of land area with permafrost. *Continuous* permafrost zones have permafrost underlying 90-100% of the landscape; *discontinuous* permafrost zones have 50-90%; *sporadic* permafrost 10-50%, and *isolated* permafrost less than 10%.

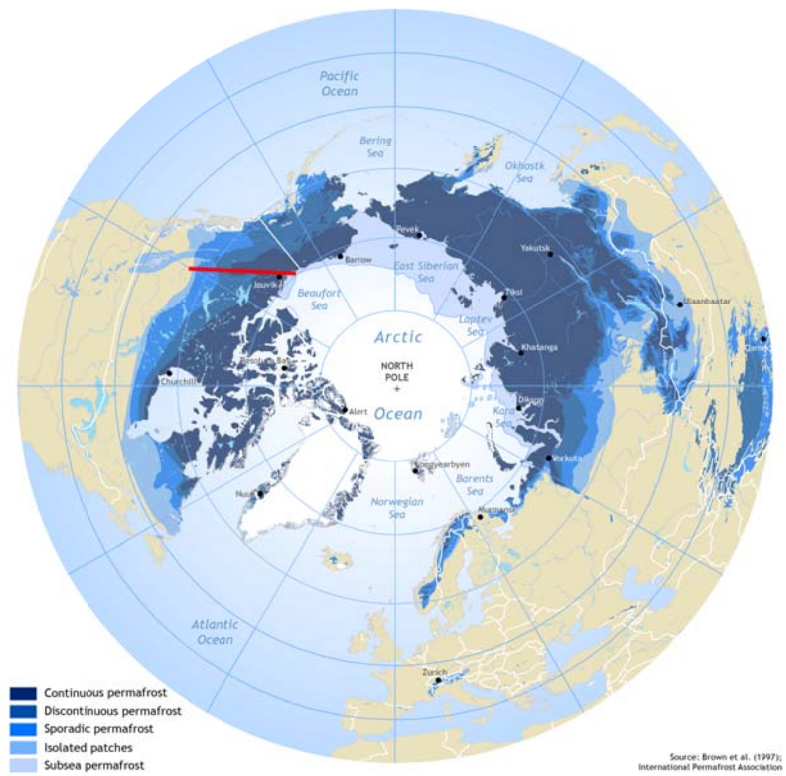

Figure 1: Much of the northern hemisphere land surface contains permafrost, divided into continuous, discontinuous, sporadic, and isolated zones. The red line shows the location of the cross section in Figure 2.

Most permafrost formed during or since the last ice age. Some relatively shallow permafrost on land extending only to depths of 30 to 70 meters formed during the last 6,000 years. Undersea permafrost along the Arctic coast in the Beaufort Sea near Alaska and Canada formed during the last ice age more than 15,000 years ago. The great ice sheets contained so much water that these regions were above sea level and exposed to cold enough conditions to form permafrost. After the ice sheets retreated, these regions were inundated and have been slowly thawing ever since.

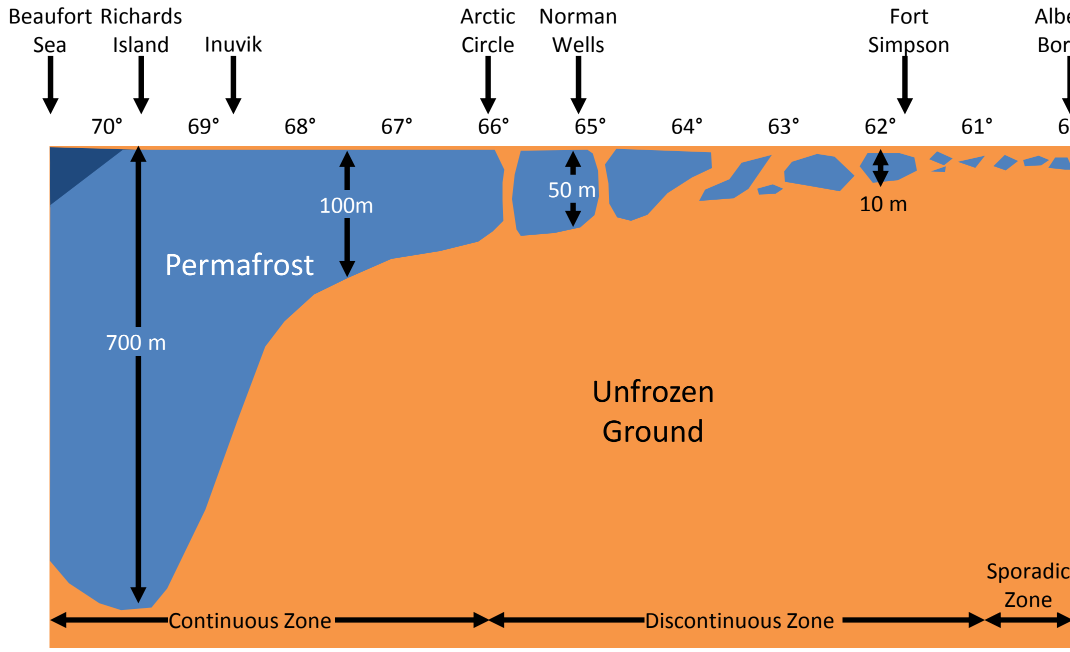

Figure 2: In this latitude cross section along the Mackenzie River basin in Canada, the permafrost changes from deep, cold, continuous permafrost along the Arctic coastline to shallow, warm sporadic permafrost in Alberta.

Permafrost is deep and continuous along the Arctic coastline where temperatures are coldest, transitioning to discontinuous and finally sporadic permafrost further south where temperatures are warmer (Figure 2). The coldest and deepest permafrost occurs where air temperatures are lowest: near the Arctic coast in Siberia and the Canadian Archipelago (Smith et al. 2010). *Cold permafrost* occurs in continuous zones with temperatures between -15 and -1 °C. *Warm permafrost* occurs in discontinuous zones with temperatures between -3 and 0 °C (Christiansen et al. 2010; Romanovsky et al. 2010a, b; Smith et al. 2010).

Air temperature decreases with altitude, resulting in permafrost formation in mountainous regions at warmer latitudes, such as the Rocky Mountains in North America, the European Alps, and the Tibetan Plateau in Asia. The distribution of permafrost in mountain is typically *discontinuous* or *sporadic*, depending on slope, orientation to the Sun, vegetation, and snow characteristics. Mountain permafrost is considered *warm permafrost*, with temperatures ranging from 0 to -5.2 °C (Sharhuu et al. 2008; Harris et al. 2009; Brown et al. 2010; Zhao et al. 2010).

The *active layer* is the surface layer of soil that thaws each summer and refreezes each winter (Figure 3). The active layer starts thawing in spring after the snow melts and continues to thaw throughout the summer, 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 the end of winter. Active layer thickness is the annual maximum thaw depth, ranging from 30 cm along the Arctic coast, to 2 meters or more in Southern Siberia, and several meters in the European Alps.

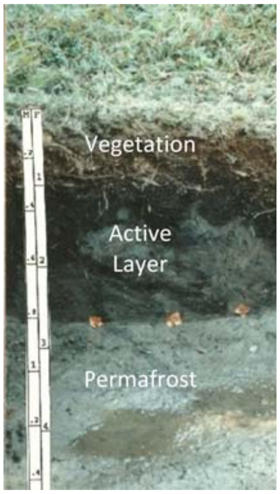

Figure 3: This photograph from the North Slope of Alaska shows a typical permafrost soil profile exposed by erosion along a river. Ice makes the permafrost appear lighter than the active layer (photo: unknown).

The *permafrost body* is the layer of perennially frozen ground, bounded on the top by the permafrost table and on the bottom by the permafrost base (Figure 4). The depth of the permafrost table is the active layer thickness. The depth of the permafrost base depends a balance between freezing from the surface and warming from the Earth's interior. Generally, regions with cold winters develop a deep permafrost base, ranging from 400 to 600 meters in northern Alaska and northern Canada to 1500 m in northern Siberian.

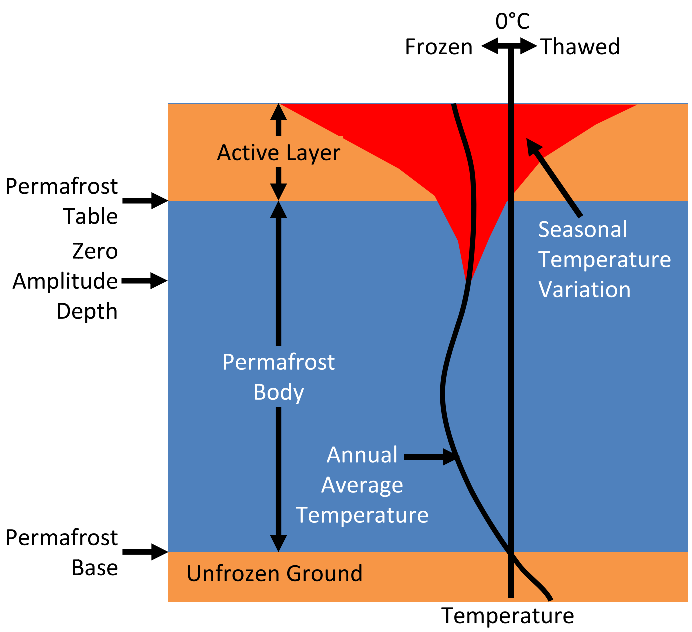

Figure 4: The annual average temperature defines the vertical structure of permafrost. The red region represents seasonal variation in ground temperature, which determines the active layer thickness and permafrost table. The permafrost body is the layer of perennially frozen ground bounded by the permafrost table and base.

Permafrost temperatures at deeper depths reflect air temperature variability at longer time scales because heat diffuses slowly through permafrost. Seasonal variability in air temperature becomes increasingly damped with depth and below the depth of zero amplitude, only changes in annual average air temperature influence permafrost temperature. The zero amplitude depth varies from a few meters in warm permafrost to 20 meters in cold permafrost (Smith et al. 2010; Romanovsky et al. 2010a). Temperatures at the zero amplitude depth reflect 20th century climate conditions, but temperatures at 400 to 800 meters depth reflect the climatic conditions at the Holocene optimum 8,000 years ago, just after the end of the last ice age (Osterkamp and Romanovsky 1999; Haeberli 2000).

Permafrost includes the contents of the soil before it was frozen, so the permafrost body can include bedrock, gravel, rocks, organic material, and sometimes animal remains. Ice acts like concrete to bind soil and rock together such that permafrost is hard, durable, and resistant to erosion, with a physical texture similar to cinder block. Thermal expansion and contraction coupled with the flow of water across the landscape can form ice layers, lenses, blocks, and wedges in the permafrost body. Plant roots cannot penetrate permafrost, so live vegetation is restricted to the active layer. Cold temperatures and annual refreezing slow the decay of dead plant material, resulting in rich, organic soil in the active layer.

1.2. What Controls Permafrost?

Air temperature is the dominant control on global permafrost distribution, followed by local snow characteristics. Any location with annual average air temperatures below freezing can form permafrost (Humlum 1998b; Stocker-Mittaz et al. 2002). Snow is mostly air and a very effective insulator, often resulting in permafrost body temperatures 5 to 10 °C warmer than winter air temperatures (Harris 2001; Luetschg et al. 2004). Snow thickness, timing, and duration influence permafrost formation. A cold location with deep snow may not form permafrost while a warmer location with no snow would form permafrost. Rock walls in alpine areas often form permafrost because they completely lack the insulating effects of snow, vegetation, debris, or talus (Gruber and Haeberli 2007). 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 crevasses, but not on sunlit ridges (Funk and Hoelzle 1992). The insulating effects of surface vegetation and organic matter often result in huge variability in active layer thickness within the space of a few meters (Humlum 1998a).

Changes in air temperature and snow cover can degrade permafrost. Permafrost degradation is any increase in active layer thickness or decrease in the areal extent of permafrost over time. As the active layer deepens, a layer of unfrozen soil called a *talik* can form above the permafrost table but below the maximum freeze depth in winter. Permafrost degradation is accompanied by erosion and other physical changes to the landscape. Permafrost is highly resistant to erosion, but the bonding strength of ice disappears when permafrost thaws, making it vulnerable to erosion. A *Thermokarst* is a depression caused by the collapse and erosion of thawed permafrost (Figure 5 and 6).

Figure 5: This is a typical thermokarst about 100 meters across and filled with water next to Pumping Station 3 along the Alaska Pipeline just south of the Brooks Range. The three meter fence has begun to collapse due to erosion (Photo: Tingjun Zhang)

Figure 6: A thermokarst formation near Fairbanks Alaska caused the trees to tilt, earning the name of 'drunken trees' (Photo: Kevin Schaefer)

1.3. Monitoring Permafrost

The primary measurements to monitor the status of permafrost are permafrost body temperature and active layer thickness. Other observations include sample drilling, remote sensing to measure changes in surface characteristics, and radar to measure surface movement, but these do not capture the thermal state of permafrost. There are two global networks to monitor permafrost: the Thermal State of Permafrost (TSP) network, which coordinates measurements of permafrost body temperature and the Circumpolar Active Layer Monitoring (CALM) network, which coordinates measurements of active layer thickness (Figure 7).

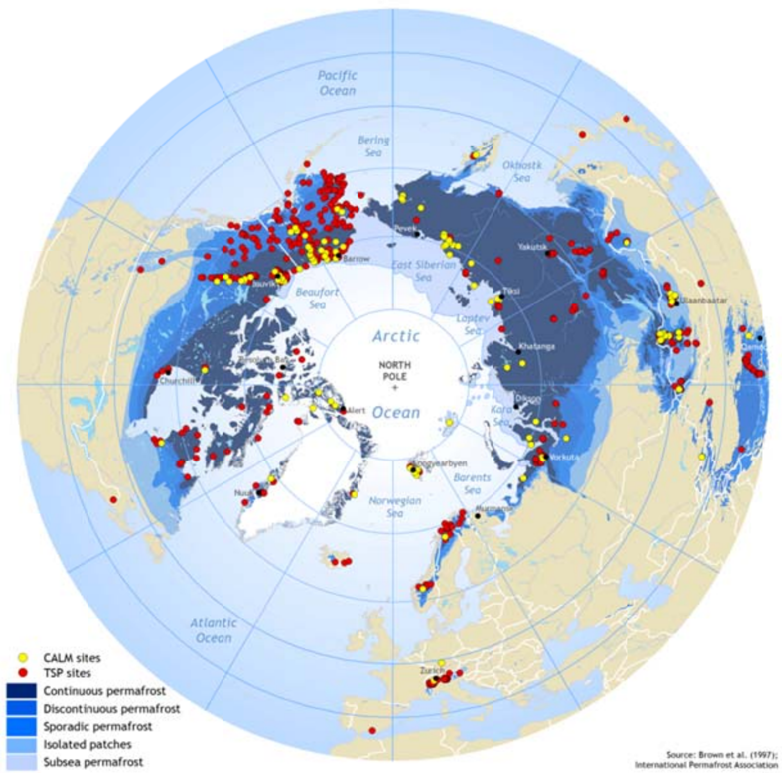

Figure 7: This map shows the sites in the Circumpolar Active Layer Monitoring (CALM) and the Thermal State of Permafrost (TSP) networks. CALM measures active layer thickness and TSP measures permafrost body temperature.

Permafrost body temperature is measured at multiple depths using boreholes in the TSP network. Boreholes are drilled down to hundreds of meters depth contain a string of temperature sensors at multiple depths. Temperature measured by these sensors may be recorded manually during site visits or recorded by computer continuously with time intervals from several hours to several days. 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 Tibetan Plateau (Brown et al. 2010).

Active layer thickness or maximum annual thaw depth and is measured in the CALM network either mechanically using a probe or electronically with a vertical array of temperature sensors. The probe is a simple metal rod sunk into the ground: when the operator hits the hard permafrost table, he marks the depth on the rod, pulls it out, and records it. 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 to the depth corresponding to 0°C using temperature sensors placed above and below the permafrost table. Mechanical probing is labor-intensive and occurs only at specified time intervals, but is relatively cheap and easy to implement. Temperature sensors provide continuous coverage over time, but are expensive to install and maintain. The CALM network measures active layer thickness at 168 sites since the 1990s (Brown et al. 2000; Streletskiy et al. 2008; Shiklomanov et al. 2010). Installation and maintenance costs restrict CALM sites to regions with reasonable access by road, plane or boat, resulting in a distinct clustering of sites along the Arctic coastline in Alaska and Central Siberia.

1.4. Current State of Permafrost

Recent warming in the Arctic and mountainous regions has degraded permafrost, with warmer permafrost temperatures and deeper active layers. Permafrost is warming in most regions with evidence of talik formation at some locations. Increased snow cover and warming permafrost resulted in massive development of new taliks in Russia, shifting the boundary between continuous and discontinuous permafrost northward 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).

Permafrost temperatures have risen over the last several decades (figure 8). Permafrost temperatures are generally coldest along the Arctic coast and decrease towards the south. In mountainous regions like the Brooks Range, altitude as well as latitude determines permafrost temperature. Cold 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. 2010a). 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 Alaska during the last 30 to 35 years (Drozdov et al. 2008; Oberman 2008; Romanovsky et al. 2010b; Smith et al. 2010). The same pattern repeats across the Arctic with cold, coastal sites warming faster than warmer or more southerly sites (Romanovsky et al. 2010a).

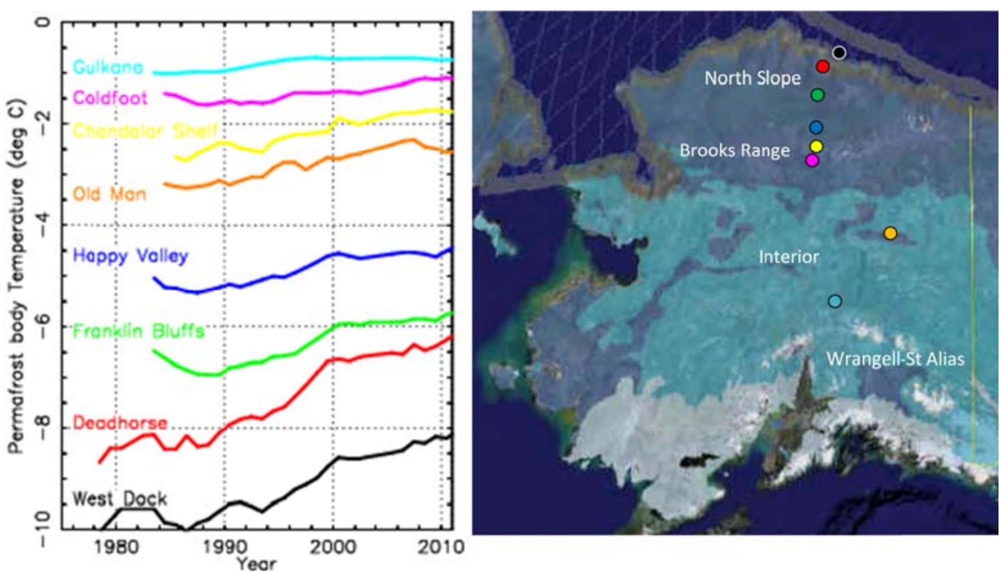

Figure 8: Permafrost body temperatures have warmed over the past 30 years, as seen in these temperature observations for north-south transect of TSP sites in Alaska.

Trends in active layer thickness are less conclusive, with some sites showing increases, but others showing no trend at all. Active layer thickness varies strongly from year to year, making the detection of long-term trends difficult (Smith et al. 2009; Popova and Shmakin 2009). Active layer thickness has increased so much near Abisko, Sweden that permafrost has essentially disappeared in several mires (Åkerman and Johansson 2008; Callaghan et al. 2010). Active layer Thickness has increased in the Russian European North, but not in West Siberia (Mazhitova 2008; Vasiliev et al. 2008). Active layer thickness has increased on the Qinghai–Tibet Plateau in response to an increase in summer air temperatures (Wu and Zhang 2010; Zhao et al. 2010). Active layer thickness has increased in the Alaskan and Canadian interior, but not along the Arctic coastline (Streletskiy et al. 2008; Shiklomanov et al. 2010; Smith et al. 2009; Burn and Kokelj, 2009; Smith et al. 2010). However, long-term trends in surface subsidence near Prudhoe Bay measured using radar indicate melting of excess ground ice (Liu et al. 2010).

2. Impact of Climate Change on Permafrost

2.1. Future Climate

The average surface air temperature in the Arctic is expected to increase by 5 to 6 °C by 2099, nearly double the global average of 3 °C (Figure 9) (IPCC 2007). This is based on the moderate, A1B scenario of future fossil fuel emissions from the Intergovernmental Panel on Climate Change (IPCC). The uncertainty is ±0.5 °C based on the spread between models. Global warming due to fossil fuel emissions is amplified in the Arctic due to reduced snow and ice cover. As temperatures rise, the highly reflective sea ice and snow melt, increasing the amount of energy absorbed by the Sun. This amplification is particularly strong in spring and fall and is called the *snow albedo feedback* (albedo is surface reflectivity). A similar effect occurs in the mountains, where warming is also occurring faster than the global average.

Precipitation is expected to increase by 30% in the Arctic based on the moderate, A1B scenario with an uncertainty of ±16% (Figure 10) (IPCC 2007). The temperate latitudes are expected to become drier while the Arctic becomes wetter. Precipitation increases 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 drop their moisture, resulting in increased precipitation. A similar effect occurs in mountainous regions, where precipitation is expected to increase 10% in winter.

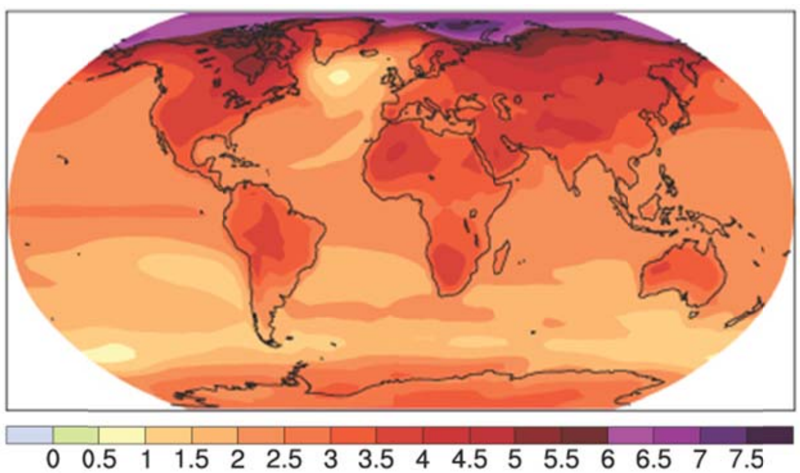

Figure 9: By 2099, the average surface air temperature in the Arctic is expected to increase by 5 to 6 C, nearly double the global average of 3 C based on this multi-model mean from the IPCC Fourth Assessment Report. The units are degrees centigrade and the changes are annual means for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999.

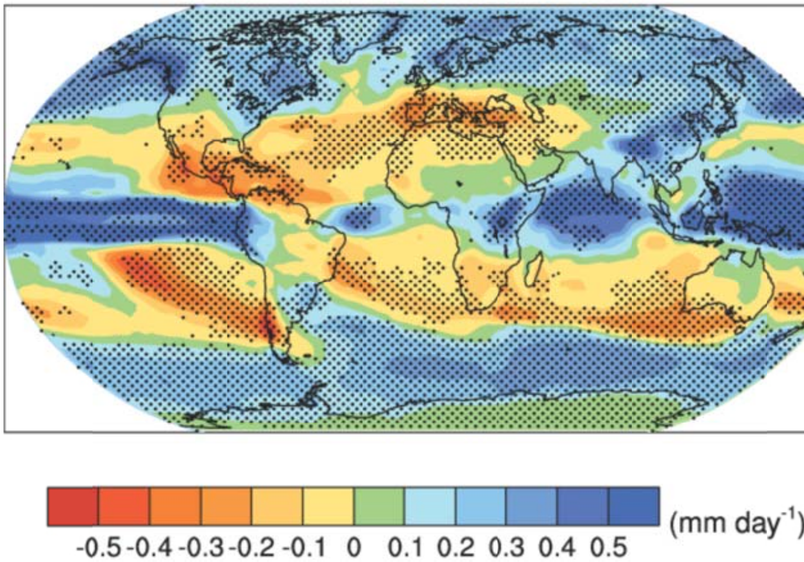

Figure 10: By 2099, precipitation is expected to increase in the Arctic and decrease in temperate zones based on this multi-model mean from the IPCC Fourth Assessment Report. The units are millimeters per day and the changes are annual means for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Stippled indicate where eight out of ten models agree.

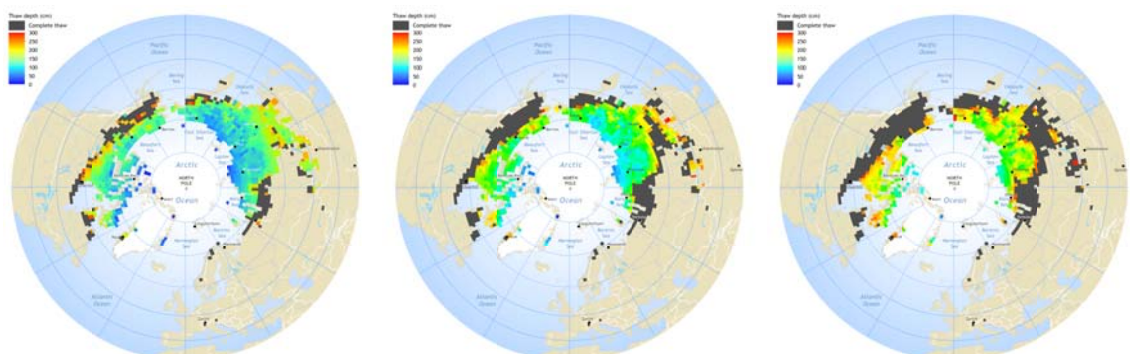

Figure 11: This model simulation shows that as temperatures rise in the future, the active layer thickness will increase and the permafrost boundary will move northward, contracting around the coldest regions in the Arctic. Black shows regions where permafrost has completely thawed. This simulation for the IPCC A1B scenario indicates a 59% loss in permafrost area by 2100 (*Schaefer et al*. 2011).

2.2. Permafrost in the Future

Projections of future permafrost degradation all agree that active layer thickness will increase and the areal extent of permafrost will decrease, but disagree on the amount (Table 1). The average loss of land area with permafrost is 44% by 2100 and the average increase in active layer thickness for areas that retain permafrost is 65 cm. The large spread in predicted permafrost degradation results from how different models represent soil and snow processes, the assumed future scenarios of fossil fuel emissions, and how strongly the model warms in response to increased atmospheric CO_2.

Permafrost degradation in response to warming follows the same basic pattern in all models: increases in active layer thickness followed by a northward movement of the permafrost boundary (Figure 11). 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). Taliks will form first along the southern margins of permafrost regions with warm permafrost (Zhang et al. 2008). As taliks expand, the permafrost becomes patchy and eventually disappears, moving the southern margins of both discontinuous and discontinuous permafrost northward and to higher elevations in mountain regions. The loss of permafrost will progress northward over time, contracting around regions with the coldest permafrost temperatures that are most resistant to thaw in Northern Siberia and the islands of Northeast Canada.

Table 1: Predicted loss of 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]
Zhang et al. [2008a]	16-20[a]	30-70
Schneider von Deimling et al. [2011]	16-46	-
Schaefer et al. [2011]	20-39	56-92
Zhang et al. [2008b]	21-24	30-80
Euskirchen et al. [2006]	27[a]	-
Koven et al. [2011]	30	30-60[a]
Saito et al. [2007]	40-57	50-300
Lawrence and Slater [2005]	60-90	50-300
Schuur et al. [2009][c]	60-90	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

[a] calculated from numbers or tables in text

[b] calculated from estimated trends

[c] calculated based on permafrost area loss from Lawrence and Slater [2005]

2.3. Ecosystem Impacts

As permafrost degrades, species composition will change, affecting animal habitat, migration, and disturbance. The sequential transition from one mix of species to another is called succession. The southern permafrost regions are covered with forest called the boreal zone while further north is tundra consisting of sedge grasses and lichen. Warming temperatures have already increased the length of the growing season, favoring the expansion of shrubs and short woody vegetation in tundra regions (Figure 12). In the boreal zone, this favors broadleaf tree species over evergreens such that the current population of black spruce and larch may recede in favor of birch, aspen, white spruce, and lodgepole pine. The overall effect is a northward migration of the tree line (ACIA 2004).

Shifts in species composition will affect animal populations that depend on specific vegetation types, such as wetlands. The permafrost table is impermeable to water, resulting in a large number of wetlands that migratory birds from around the world use as summer breeding grounds. These lakes will drain as permafrost thaws (Marsh and Neumann 2001; Prowse et al. 2006) potentially resulting in reduced habitat for waterfowl (Figure 13). Sediment displaced from thawing permafrost by thermokarst erosion will disrupt aquatic habitat such as streams and rivers, adversely affecting the fish that inhabit them.

As the active layer deepens and surface lakes drain, the soil will become drier, increasing the intensity and frequency of naturally occurring fire and insect disturbances. For example, cold winters have traditionally kept pine bark beetles in check, but recent warming trends have led to an explosion in the beetle population with massive infestations in western Canada (Aukema et al. 2006). Fire in boreal forests has increased in intensity and frequency recently (Turetsky 2011), and could become more common in tundra regions (Mack et al. 2011). Increased disturbance intensity and frequency will accelerate the succession in ecological systems.

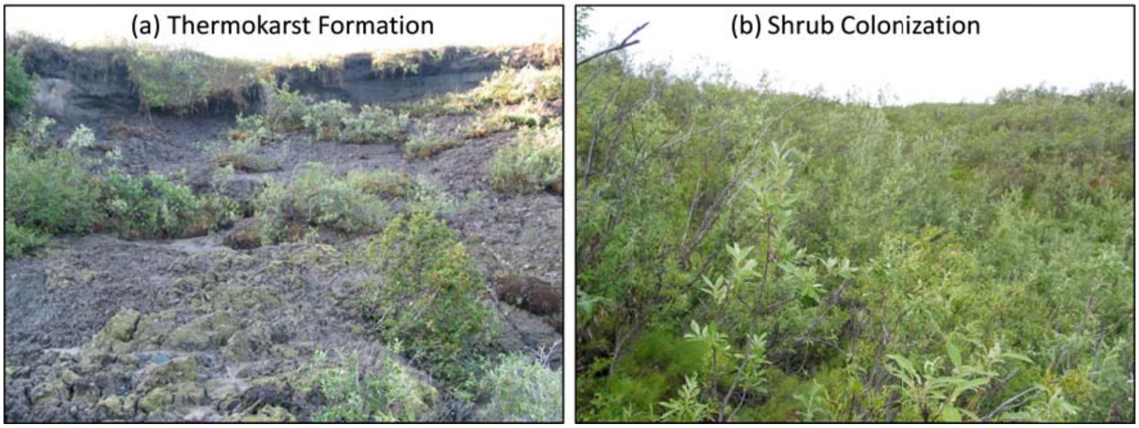

Figure 12: Warmer temperatures caused permafrost on this hillside in Alaska to thaw and erode, creating a thermokarst. Longer growing seasons associated with warmer temperatures then favored colonization of the thermokarst by woody shrubs (Photos: Edward Schuur).

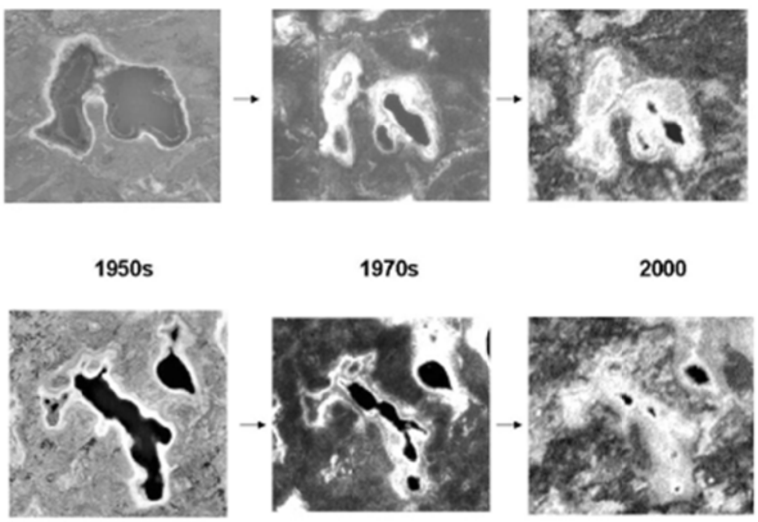

Figure 13: This series of aerial photographs in the Yukon Flats National Wildlife Refuge in Alaska show that as the thickness of the active layer increases, the lakes shrink and drain like pulling the plug on a tub (Riordan et al. 2006).

2.4. Natural Hazards

Permafrost degradation associated with a warming climate will increase risks associated with rock fall, debris flow, and erosion. Ice acts as cement to bind soil and rock together to make permafrost highly erosion resistant and stable. However, if the permafrost warms and thaws, the "cement" softens and drains away, making thawing permafrost vulnerable to erosion or sudden collapse (Kääb et al. 2007).

Thawing permafrost in steep mountain terrain increases the risk of rock fall and debris flow (Harris et al. 2001). Talus and rock 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). Rock falls and debris flows 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). Future warming will thaw mountain permafrost and the area vulnerable to rock fall and debris flows will expand as the permafrost line climbs to higher altitudes (Haeberli and Burn 2002; Haeberli and Hohmann 2008).

Climate change in the Arctic is expected to increase erosion rates along the Arctic coastline, lake shores, and river beds (Figure 15). Permafrost contains ice layers, wedges, and lenses which, when melted and drained, collapse to form thermokarsk that are highly vulnerable to erosion. The Arctic coastline has already retreated several meters in the past few decades due to warming permafrost and associated thermokarst coupled with increased wave action from rising sea levels, reduced sea ice, and increased storm impacts (Lantuit and Pollard 2008; Lantuit et al. 2011). Similar processes occur along riverbeds and lake shores throughout permafrost regions.

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

Figure 15: Warming permafrost softens, 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 dissolve (photo: Christopher Arp).

2.5. Societal and Economic Impacts

Infrastructure damage in the Arctic and mountainous regions could be significant (Figures 16 and 17). Buildings, roads, pipelines, railways, power lines, and similar infrastructure were all built assuming that the solid foundation of permafrost would not change. In fact, building practices in the Arctic are designed to preserve and prevent thawing of permafrost. However, thawing permafrost is structurally weak, creating thermokarst and foundational settling that can damage or even destroy infrastructure. Increased rock falls and erosion in mountain regions could have severe impacts on nearby settlements, roads, and railways. Warming in Arctic and mountain permafrost has already caused damage to buildings, transportation networks, pipelines, and other miscellaneous structures (Instanes and Anisimov 2008). Infrastructure failure can have dramatic environmental impacts, as seen in the 1994 breakdown of the pipeline to the Vozei oilfield in Siberia, which resulted in a spill of 160,000 tons of oil, the world's largest terrestrial oil spill.

Repair, replacement, or adaptation of damaged infrastructure will require substantial financial resources. The impacts of 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). Most settlements in the Arctic lie on the coast, where strong erosion rates place structures and roads at risk and may force the relocation of settlements at considerable cost (Figure 18) (Forbes 2011). These changes will impact 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). The Russian Federation has by far the greatest number of people living in permafrost regions and will bear the brunt of costs associated with infrastructure repair or replacement.

Figure 16: 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 17: Permafrost thawing near the base of the support pillars caused this bridge on Qinghai-Xizang Highway in Tibet to collapse (photo: Tingjun Zhang).

Figure 18: Coastal erosion of permafrost resulted in the complete destruction of this house in Shishmaref, Alaska (photo: TBD).

3. Impacts of Thawing Permafrost on Climate Change

3.1. Frozen Carbon Stocks

Permafrost contains nearly twice as much carbon as is currently in the atmosphere that has been frozen for thousands of years (Figure 19). One gigaton is a trillion kilograms of carbon. Permafrost contains an estimated 1466 Gt of frozen carbon (Tarnocai et al. 2009), while the atmosphere currently contains 850 Gt of carbon, corresponding to an atmospheric CO_2 concentration of ~390 ppm. Half of this carbon is frozen in permafrost within the top 3 m of soil, and the rest is in highly localized deposits that can extend down to 30 m depth. The age of this organic material increases with depth, ranging from 1,000 to 32,000 years (Dutta et al. 2006; Zimov et al. 2006a).

This frozen carbon 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 buildup slowly increased soil depth on time scales of decades to millennia (Schuur et al. 2008). Roots 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). Mixing of the soil during repeated freeze thaw cycles (cryoturbation) 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 carbon consists of plant roots and partially decayed organic material. Decay stops once the soil is frozen, so this organic matter has been preserved, frozen in permafrost, for thousands of years.

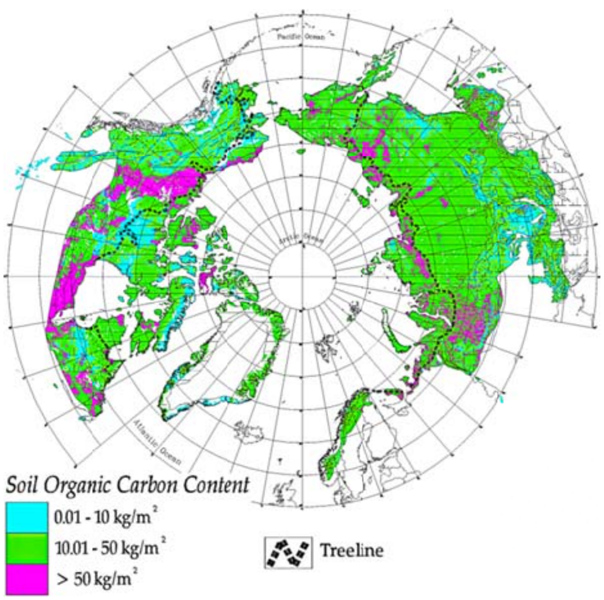

Figure 19: Nearly all permafrost contains frozen grass roots and organic matter, adding up to 1466 gigatonnes of frozen carbon in the Arctic, nearly twice as much as currently in the atmosphere (Tarnocai et al. 2009).

3.2. The Permafrost Carbon Feedback

If the permafrost thaws out, all this organic material will decay and end up in the atmosphere as CO_2 or methane, amplifying the warming due to the burning of fossil fuels (Figure 20) (Zimov et al. 2006b). Raising air temperatures in the next century will degrade the permafrost, thawing some portion of the permafrost carbon. Once thawed, microbial decay will resume and eventually the organic matter will end up in the atmosphere as additional CO_2 and methane. This will amplify the rate of atmospheric warming due to fossil fuel emissions and accelerate permafrost degradation. This amplification of surface warming due to carbon emissions from thawing permafrost is called the permafrost carbon feedback. Like the burning of fossil fuels, the permafrost carbon feedback is irreversible: once thawed and released into the atmosphere, there is no way to put the carbon back into the permafrost.

Available predictions indicate huge carbon emissions from thawing permafrost (Table 2). Up to half of the frozen carbon will thaw out, decay, and eventually end up in the atmosphere. Extensive wetlands in the Arctic imply that nearly 3% of the permafrost carbon emissions will be methane, which is 20 times more potent a greenhouse gas than CO_2 (Schuur et al. 2011). Permafrost carbon emissions could cancel out a significant portion of the global land uptake of atmospheric CO_2 (Schaefer et al. 2011). The effect of so much CO_2 and methane on global climate is not clear, since none of the projections in the IPCC Fifth Assessment Report include the permafrost carbon feedback.

Global strategies to reduce fossil fuel emissions should include carbon emissions from thawing permafrost. Organic matter decays slowly in the Arctic and permafrost carbon emissions will continue for decades and even centuries after the permafrost stops thawing (Figure 21). Half or more of permafrost carbon emissions will occur after 2100, so long-term atmospheric CO_2 concentration, and thus the climate, are determined by both fossil fuel and permafrost carbon emissions. Strategies to address climate change set a target atmospheric CO_2 concentration corresponding to a desired climate. 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). The projections of permafrost emissions in Table 2 account for 15% to 50% of total emissions, leaving only 50-85% for fossil fuels. Failure to account for permafrost carbon emissions will result in overshooting any target atmospheric CO_2 concentration, resulting in a warmer climate than desired.

Table 2: Predictions of total permafrost carbon emissions.

Study	Permafrost Carbon Emissions (Gt C)		
	2100	2200	2300
Schuur et al. [2011]	306	na	706
Schaefer et al. [2011]	104	190	na
Schuur et al. [2009][a]	85	na	na
Koven et al. [2011]	62	na	na
Schneider von Deimling et al. [2011]	26	320	529

[a] calculated from emission rates in the paper

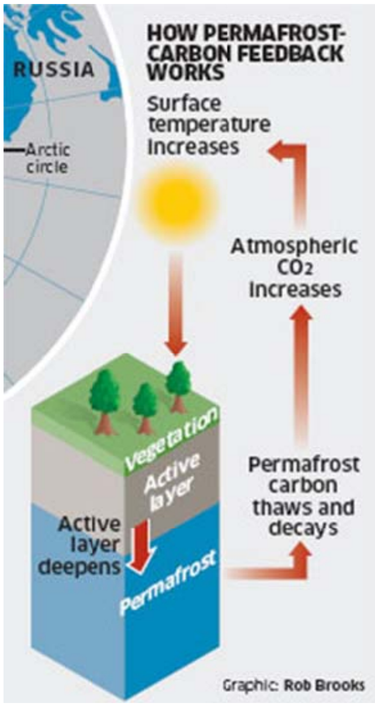

Figure 20: The permafrost carbon feedback is an amplification of surface warming due to the thaw, decay and ultimate release into the atmosphere of carbon that is currently frozen in permafrost.

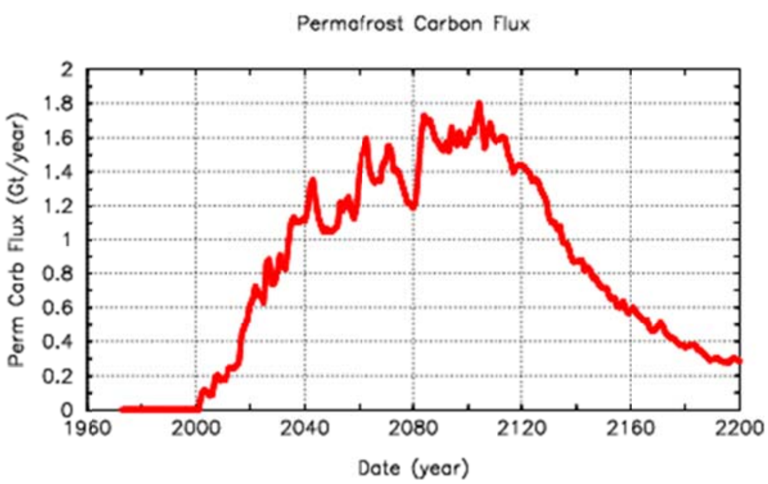

Figure 21: Annual carbon emissions from thawing permafrost can continue for decades or even centuries after permafrost stops thawing. This estimate of permafrost carbon emissions is based on the IPCC A1B scenario, where warming, and thus permafrost thaw, stops in 2100 (Schaefer et al. 2011).

4. Policy Recommendations

Institutionalize Permafrost Monitoring Networks

National governments should institutionalize and run the TSP and CALM networks to monitor permafrost, analogous to weather monitoring stations. The TSP and CALM networks are currently run by independent research teams with different objectives and instruments at each site. The networks focus on research and are not adequate to monitor permafrost in a standard way suitable for policy decisions. Funding is small and irregular, making it difficult to standardize measurements and expand the networks. The TSP network expanded during the 2007-2008 International Polar Year because of regional efforts funded by national funding agencies. Portions of the TSP have been institutionalized in Switzerland and China, but this is not adequate to globally monitor permafrost. The TSP and CALM networks are currently managed by the International Permafrost Association through the Global Terrestrial Network for Permafrost. They should be made part of international climate monitoring programs and coordinated by the World Meteorological Organization.

Allocate for Permafrost Carbon Emissions

Global treaties to reduce fossil fuel emissions should include a 15% annual allocation to account for the carbon emissions from thawing permafrost. Treaties under negotiation emphasize annual emission targets per country or region corresponding to a target atmospheric CO_2 concentration in 2100. Agreeing to such treaties means that we as a global society agree to move towards a “desired” climate corresponding to the target CO_2 concentration. The target CO_2 concentration places an upper limit on the total, irreversible CO_2 emissions into the atmosphere. Current projections indicate permafrost carbon fluxes approximately 15% of total flux. Failure to account for carbon emissions from thawing permafrost will result in overshooting the target CO_2 concentration, resulting in a warmer climate than desired.

Plan for Adaptation

Nations with substantial permafrost should plan for the risks, damage, and mitigation of permafrost degradation. Individual nations should identify regions especially vulnerable permafrost degradation. Within these regions, individual nations should identify at-risk structures and infrastructure and recruit economists to estimate repair, replacement, and mitigation costs. Engineers and scientists should develop or adapt 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.

Commission Special Report on Permafrost

The IPCC should commision a special assessment report focusing on potential permafrost degradation and the influence of the permafrost carbon feedback on global climate. None of the global climate projections that included in the IPCC Fifth Assessment Report include the effects of the permafrost carbon feedback. The IPCC will release the Fifth Assessment Report in 2013, but to make deadlines, participating model teams froze new model development in 2009, before the potential effects of the permafrost carbon feedback were identified. Nearly all the models included in the Fifth Assessment Report are capable of simulating permafrost, but the key information on simulated soil temperature and active layer thickness are not saved. The Fifth Assessment Report will guide global policy on climate change for the next decade, but without a special report on permafrost, it will lack the permafrost carbon feedback and its effect on climate.

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7. Glossary

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

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

Cold permafrost: regions where the temperature of the permafrost body is between -15 and -1 °C.

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

Cryoturbation: the mixing of soil due to the expansion and contraction of soil water during annual freeze/thaw cycles.

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

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

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 carbon: organic matter currently frozen in permafrost.

Permafrost degradation: any increase in active layer thickness, thinning of the permafrost body, 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.

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

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 of permanently thawed soil above the permafrost layer and below the active layer.

Thermokarst: a local subsidence or soil collapse due to the melting of ice and subsequent drainage of soil water from permafrost.

Warm permafrost: regions where the temperature of the permafrost body varies between -3 and 0 °C.