PERMAFROST
SLOW-MOTION MELTDOWN

PUBLISHED BY THE WWF GLOBAL ARCTIC PROGRAMME
PERMAFROST

Contents

EDITORIAL It's not permanent 3
IN BRIEF 4
TED SCHUUR Climate effects 6

CIRCUMPOLAR STATUS REPORT 8-19
MIKHAIL ZHELEZNIK and PAVEL KONSTANTINOV Russia 9
CHRIS BURN Canada 11
JONAS ÅKERMAN Sweden 12
BERND ETZELMÜLLER Norway 13
HANNE HVIDTFELDT CHRISTIANSEN Svalbard (Norway) 15
BERND ETZELMÜLLE Iceland 16
STEPHEN D. GURNEY and JUKKA KÄYHKÖ Finland 17
BO ELBERLING Greenland 18
KENJI YOSHIKAWA United States 19
BRONWYN BENKERT Shifting sands – living on permafrost 20
KEVIN SCHAEFER The tipping point 22
JEAN HOLLOWAY The impact of forest fires 24
FUJUN NIU Building on permafrost in the “Third Pole” 26

THE PICTURE 28

The Circle is published quarterly by the WWF Global Arctic Programme. Reproduction and quotation with appropriate credit are encouraged. Articles by non-affiliated sources do not necessarily reflect the views or policies of WWF. Send change of address and subscription queries to the address on the right. We reserve the right to edit letters for publication, and assume no responsibility for unsolicited material.

Publisher:
WWF Global Arctic Programme
8th floor, 275 Slater St., Ottawa,
ON, Canada K1P 5H9.
Tel: +1 613-232-8706
Fax: +1 613-232-4181
Internet: www.panda.org/arctic
ISSN 2073-980X = The Circle

Date of publication: October 2015.

Editor in Chief: Clive Tesar,
CTesar@WWFCanada.org

Managing Editor: Becky Rynor,
brynor@uniserve.com

Design and production:
Film & Form/Ketill Berger,
ketill.berger@filmform.no

Printed by St. Joseph Communications

COVER: Houses in Shishmaref, Alaska, collapsing due to coastal erosion. The melting of permafrost destabilizes the shoreline and makes the earth more vulnerable to erosion.
Photo: Lawrence Halip: www.grida.no

ABOVE: To create their shelter Alaska marmots burrow into permafrost soil containing tundra vegetation.
Photo: Erin McKittrick, Bretwood Higman, Ground Truth Trekking/ Creative Commons

Thank you for your interest in The Circle. Many of our subscribers have moved to an e-version. To receive an electronic copy in your email instead of a paper copy, please write to us at gap@wwfcanada.org and help us reduce our costs and footprint.
It’s not permanent

PERMAFROST AROUND THE ARCTIC is changing. It is warming virtually everywhere as the climate warms, and in some places, it’s thawing. This edition of The Circle explores why this is happening, what happens when permafrost thaws, how it can be mitigated and why the rest of the world should be concerned about it.

Changes to permafrost occur within the ground so they’re challenging to track across the vast areas of the Arctic. We can’t easily use satellite remote sensing, for example, to know what is happening. During the last International Polar Year, scientists from the International Permafrost Association created a snapshot of permafrost temperatures recorded in boreholes all across the North. This work is continuing in the Global Terrestrial Network on Permafrost (GTN-P) whose goal is to track changing ground temperatures. You will read more about this vital research in our Circumpolar Status Report as each Arctic nation brings us up to date on permafrost in their countries.

Permafrost is warming rapidly in the High Arctic and more slowly where it’s already near 0°C with the extra heat entering the surface being used to change ground ice into water. Because permafrost responds to climate, these trends are predicted to continue over the decades to come as the climate warms.

Even if it’s out of sight, permafrost has a way of bringing its thermal state to our attention. Numerous massive landslides have developed recently in the Peel Plateau of Canada’s Northwest Territories, apparently triggered by greater summer rainfall. Jean Holloway also tells us about the escalating effects of increasing numbers of forest fires on permafrost. Meanwhile, the northernmost 200 km of the Alaska Highway in the Yukon costs millions of dollars per year to maintain because permafrost is thawing beneath the road; tourists bumping along in their recreational vehicles as well as highway engineers know that these problems keep coming back. Erosion along coasts with ice-rich permafrost appears to be increasing, threatening communities across the Arctic. But all of these impacts are chiefly felt by the northern-ers who live in permafrost areas and by governments and industry who must pay for the increasing infrastructure costs associated with development in the Arctic. A report by Fujun Niu illustrates how China has made significant advances in building on this increasingly unstable surface. But why should the rest of the world care?

In 2009, a group of international researchers put together an estimate of how much carbon is stored in permafrost regions, drawing on samples from around the Arctic. The number was astonishing: 1670 Pg or about twice the current amount in the atmosphere. Almost all of this carbon is currently in cold storage, but the obvious unknown is whether it can be released, and if so, how much will it contribute to future global warming? The risk is of a positive feedback loop in which climate warming causes permafrost thaw and carbon is released into the atmosphere either as carbon dioxide or methane as the previously frozen organic matter is broken down by microbial action.

As Kevin Schaefer and Ted Schuur report, this increases the concentration of greenhouse gases in the atmosphere which leads to further warming and faster thaw of permafrost.

There has been a great deal of research on the links in this permafrost and carbon release chain in recent years, but it would be fair to say the jury is still out. What we know is disturbing because permafrost thaw is likely to be irreversible. On the other hand, it takes time to warm and then thaw permafrost so there is still an opportunity to act.

Members of the Arctic Council know that it’s costly to cope with permafrost. But the price paid by the global community for accelerating permafrost thaw could well be far greater.

ANTONI LEWKOWICZ is a Professor in the Department of Geography at the University of Ottawa. He has researched permafrost in the Arctic and Subarctic for nearly 40 years and is currently President of the International Permafrost Association.
Thawing permafrost could cost $43 trillion by end of century

A NEW STUDY estimates emissions from thawing permafrost will cost US$43 trillion in lost agriculture, ecosystems and health impacts by the end of this century.

The study, released by Cambridge University and the National Snow and Ice Data Centre, says permafrost is believed to contain 1,700 gigatonnes – each gigatonne is a billion tonnes – of carbon. When permafrost thaws, carbon dioxide and methane locked inside is released.

Co-author Chris Hope says researchers calculated economic costs by looking at the direct effects on gross domestic product, as well as indirect effects “such as losses to ecosystems, inundation from sea level rise, and an increase in the chance of climate catastrophe.”

Deaths from heat stroke in Europe are one specific example of the health-related effects of thawing permafrost. Hope says until this study there have been no estimates on the cost of those emissions on the economy.

“This is just one more factor that indicates that we really need to do something,” says researcher Kevin Schaefer, who worked on the project. He says the only way to stop the permafrost from thawing is to reduce emissions.

The $43 trillion US estimate is in addition to previous studies, which have put the economic impacts of climate change at more than $300 trillion by the year 2200. Eighty per cent of economic impacts will be felt in developing countries.

Shell stops Arctic activity after ‘disappointing’ tests

ROYAL DUTCH SHELL has stopped Arctic oil and gas exploration off the coast of Alaska after “disappointing” results from a key well in the Chukchi Sea.

The company said it would end exploration off Alaska “for the foreseeable future” after it failed to find sufficient amounts of oil and gas in the Burger J well to warrant further exploration but it has not given up its Arctic leases. “Shell continues to see important exploration potential in the basin, and the area is likely to ultimately be of strategic importance to Alaska and the US,” said Marvin Odum, president of Shell USA. The company has spent about US $7bn on Arctic offshore development in the Chukchi and Beaufort seas.

WWF opposes drilling in the Chukchi Sea, given the environmental and cultural values of this pristine and complex marine ecosystem, crucial for wildlife, fisheries and local people. “The world
New study chronicles four years in the life of walruses

WWF-RUSSIA and the Marine Mammal Council have completed a study of the Atlantic walrus population in the Barents Sea, north of Norway and Russia where wildlife is under growing pressure from development.

“The southeastern part of the Barents Sea is faced with the rapid development of shipping and mineral extraction. All this could put walruses at risk”, says Margarita Puhova, coordinator for marine biodiversity at WWF Russia.

Ten years ago, we had very little reliable data on the current state of the population – only scraps of information from a single expedition.”

WWF has recently helped fund several projects in Greenland including initiatives around the Last Ice Area, and a polar bear patrol in east Greenland.

needs to stop expending resources trying to extract more fossil fuels from the most hostile and remote places on the planet, and risking irreversible environmental damage at the same time,” said Brad Ack, WWF-US senior vice president for oceans, “We urgently need to redirect all of that energy to accelerate our nation’s and the world’s transition to a future powered by clean, renewable energy”

WWF opens office in Greenland

WWF has become the first global conservation organization to open an office in Greenland.

“It has always been a top priority that the staff we employ for our Arctic work has a thorough knowledge of Greenland and the Arctic,” says Gitte Seeberg, Secretary General of WWF Denmark. “Our experience in the Arctic has shown that having people on the ground of the place you are talking about helps build dialogue and relationships.”

Biologist Kaare Winther Hansen has lived and worked in Greenland for several years and will staff the office in the capital city of Nuuk.

“I am delighted to represent WWF and participate in the ongoing debate about the environment, nature and sustainable development in Greenland,” she says. “I look forward to participating in discussions on how we can develop Greenland for Greenlanders while maintaining traditional livelihoods and values.”

WWF has also recently funded several projects in Greenland including initiatives around the Last Ice Area, and a polar bear patrol in east Greenland.

Bearing Witness

WWF has commissioned a sculpture by renowned Danish artist Jens Galschiot to focus attention on climate change and its consequences for the Arctic and its wildlife. The sculpture will be unveiled and exhibited at the annual Conference of Parties (COP21) also known as the 2015 Paris Climate Conference. The sculpture is named ‘Unbearable’ and depicts a polar bear being pierced by a graph of accumulated carbon in the atmosphere.

COP21 will be one of the largest international conferences on climate change ever held, with an expected attendance of close to 50,000 participants from government, intergovernmental organisations, UN agencies, NGOs and civil society.

COP21 will be one of the largest international conferences on climate change ever held, with an expected attendance of close to 50,000 participants from government, intergovernmental organisations, UN agencies, NGOs and civil society.
Soils from the northern circumpolar permafrost zone contain almost twice as much carbon as is currently in the atmosphere. Temperatures in this region are already rising twice as fast as the global average and are expected to keep warming as a result of emissions of carbon from coal, oil, gas and deforestation around the globe. TED SCHUUR says a warmer climate causes permafrost ground to thaw, and exposes organic carbon to decomposition by soil microbes.
The tremendous quantities of permafrost carbon stored in the north. The known pool of permafrost carbon is 1330-1580 billion tons, accounting both for carbon in the surface three meters of soil, and for carbon that is stored much deeper. These deep deposits occur in areas of Siberia and Alaska that remained unglaciated during the last Ice Age, as well as in Arctic river deltas. Even beyond the deep carbon that has been documented, there are permafrost carbon pools that at this point still remain largely a mystery. In particular, there are deep permafrost sediments outside of Siberia and Alaska as well as permafrost that is now beneath the ocean. Ocean permafrost is located on the shallow Arctic sea shelves that were exposed during the last glacial period when the ocean was 120 meters lower than today, since ground must be exposed to frigid air temperatures in order for permafrost to form. These additional deposits are poorly quantified but could add several hundred billions tons more carbon to the known permafrost carbon pool described here.

The critical question is how much of this permafrost carbon is susceptible to climate change on a timescale that matters to our decision-making. The strength of the permafrost carbon feedback to climate depends on how much carbon is released, how fast it happens, and the form of carbon (carbon dioxide, methane) that makes it to the atmosphere. Research has measured the tremendous quantities of carbon in permafrost soils, but some of this carbon is stored deep in permafrost and will take time before a warmer climate can affect temperatures deep in the ground. Even when thawed, some fraction of organic carbon is susceptible to rapid breakdown and release as greenhouse gases, while another fraction will remain in soil even when the temperatures rise due to other factors that preserve carbon in soils.

Still, initial estimates of potential greenhouse gas release point towards the potential for significant emissions of Carbon from permafrost to the atmosphere in a warmer world. The most recent scientific efforts put the vulnerable fraction about 5-15% of the vast permafrost carbon pool in scenarios where human-caused climate change progresses on its current trajectory. While that vulnerable fraction is on the smaller rather than the larger side of the total pool, it still would result in the addition of billions of tons of additional carbon into the atmosphere. Ten percent of the known terrestrial permafrost carbon pool is equivalent to 130–160 billion tons carbon. That amount, if released primarily in the form of CO₂ at a constant rate over a century, would make it similar in magnitude to other historically important biospheric sources, such as deforestation, but far less than current and future fossil-fuel emissions. Considering CH₄ as a fraction of permafrost carbon release would increase the warming impact of these emissions.

Permafrost carbon emissions are likely to occur over decades and centuries as the Arctic warms, making climate change happen even faster than we project on the basis of emissions from human activities alone. Because of momentum in the system and the continued warming and thawing of permafrost, permafrost carbon emissions are likely not only during this century but also beyond. Although never likely to overshadow emissions from fossil fuel, each additional ton of carbon released from the permafrost region to the atmosphere will probably incur additional costs to society. Understanding of the magnitude and timing of permafrost carbon emissions based on new observations and the synthesis of existing data needs to be integrated into policy decisions about the management of carbon in a warming world.
Permafrost is defined as ground, soil or rock, including ice or organic material, that remains at or below 0°C for at least two consecutive years. The regions in which permafrost occurs occupy approximately 24% (23 million km²) of the northern hemisphere.
PERMAFROST UNDERLIES more than one half of the land surface of Russia. Its thickness varies from a few meters to 1200 m. Permafrost occurs very close to the surface, from a few tens of centimeters in the north to a few meters in the south, and is therefore sensitive to climate change. The relationship between permafrost and climate is very complex. In addition to air temperature, permafrost is strongly affected by snow cover (depth, density, and duration), rainfall amount, vegetation, type and properties of soil or rock, and surface energy exchanges.

Monitoring observations in Russia over the last 30-40 years indicate regional differences in permafrost temperature trends. Some regions show no change, while others show warming of varying magnitude due to variations in microclimatic conditions. In the lowlands covered by taiga forests, snow depth is a major control on the ground thermal regime. In the Arctic coastal areas and high mountains, strong winds result in a dense snow cover, making other factors, such as the winter air temperature and the duration of snow cover, more important. In
permafrost areas receiving little precipitation, the amount of rainfall plays an important role in determining ground temperatures. The response of permafrost to recent warming is also greatly influenced by vegetation although its role is the least understood.

Weather station records for northern Russia indicate an increase in mean annual air temperature of 0.7 to 3.0°C over the last 30 years, again causing regionally different responses of permafrost temperature.

The largest changes occurred in the north-east of the European part of Russia and in West Siberia, where the cycles of warmer air temperature and greater snow depth generally coincided. Since 2000 onwards permafrost temperatures have been increasing. In northern West Siberia, monitoring observations indicate that permafrost warming varies across the natural zones. Little change has been observed in the tundra zone, where ground temperatures exhibit strong fluctuations with a very small increasing trend. The greatest warming has occurred in the southern forest-tundra and northern taiga zones. Deepening of the permafrost table to depths of 5-7 m and formation of residual thaw layers in permafrost have also been reported in parts of this region.

In East Siberia and the Russian Far East, some sites show no change in near-surface permafrost temperatures, while others have warmed. The rates of change have been variable, with greatest warming in the alpine and subalpine zones in southern Yakutia and significant warming in the southern part of the Chukotka Peninsula. A slight increase in ground temperature has been observed recently on the northern coast of the Sea of Okhotsk and in the Arctic coastal areas of Yakutia. Central Yakutia has experienced a strong warming of air temperature over the last 30 years. However, permafrost temperatures show no long-term trend, because the cycles of higher air temperature and the cycles of greater snow depth did not coincide. This region is characterized by short-term interannual variations of large amplitudes.

Seasonal thaw depth is another important indicator of permafrost stability. Analysis of data from the Circumpolar Active Layer Monitoring (CALM) program for the last 15 years indicates that long-term active layer dynamics in Russia varies by region. Increasing trends in seasonal thaw depth have been observed in the Russian European North, the forest-tundra and northern taiga zones of West Siberia, and the northern Far East, as well as at some locations in East Siberia. The tundra zone of West Siberia, central Yakutia, and parts of East Siberia have shown no long-term changes in active-layer thickness.

In natural settings, thawing of permafrost from the top and areal reduction are occurring most intensively along the southern limit of the Siberian permafrost region (where ground temperatures are –1°C or higher). In areas affected by human activities, local permafrost degradation is observed throughout the region. In recent years, manifestations of permafrost degradation (thermokarst, thermal erosion, etc.) have been observed along linear engineering structures, mining areas, agricultural lands and fire-affected areas. The initial cause for these changes are vegetation disturbance, disruption of surface and subsurface drainage, and, of course, climate warming.
The map of permafrost in Canada shows that about half of the country is in the area affected by permafrost. The permafrost region is divided into four zones: continuous permafrost, where over 90% of the land surface is underlain by perennially frozen ground; widespread discontinuous permafrost (50–90%); sporadic discontinuous (10-50%); and the zone of isolated patches of permafrost (less than 10%). In addition, permafrost may be found at high elevation in the eastern and western mountains and offshore where the continental shelf was exposed during the last glaciation. The latter observation shows that, in places, permafrost has been present for millennia. In total, one third of the country is underlain by perennially frozen ground.

The thickness of permafrost varies from one or two metres at the southern margins to hundreds of metres in the continuous permafrost zone. Ground temperatures in permafrost are generally lowest near the surface of the ground and increase with depth until 0°C is reached. The annual mean temperature near the surface is commonly above -2°C in the discontinuous permafrost zones, but in continuous permafrost, measured values fall as low as -14°C. Throughout the country, annual mean temperatures in the uppermost layers of permafrost have increased in the last 20 years, in association with climate warming throughout the North. The warming has been up to 2°C. As a result, in the regions where it has been continuing longest, the signs of warming can be detected to depths of over 100 m.

Climate warming itself has not yet provoked a major terrain response, although some effects have become evident in the last five years. These are expected to increase in magnitude and

**Canada**

By CHRIS BURN

**THE MAP** of permafrost in Canada shows that about half of the country is in the area affected by permafrost. The permafrost region is divided into four zones: continuous permafrost, where over 90% of the land surface is underlain by perennially frozen ground; widespread discontinuous permafrost (50–90%); sporadic discontinuous (10-50%); and the zone of isolated patches of permafrost (less than 10%). In addition, permafrost may be found at high elevation in the eastern and western mountains and offshore where the continental shelf was exposed during the last glaciation. The latter observation shows that, in places, permafrost has been present for millennia. In total, one third of the country is underlain by perennially frozen ground.

The thickness of permafrost varies from one or two metres at the southern margins to hundreds of metres in the continuous permafrost zone. Ground temperatures in permafrost are generally lowest near the surface of the ground and increase with depth until 0°C is reached. The annual mean temperature near the surface is commonly above -2°C in the discontinuous permafrost zones, but in continuous permafrost, measured values fall as low as -14°C. Throughout the country, annual mean temperatures in the uppermost layers of permafrost have increased in the last 20 years, in association with climate warming throughout the North. The warming has been up to 2°C. As a result, in the regions where it has been continuing longest, the signs of warming can be detected to depths of over 100 m.

Climate warming itself has not yet provoked a major terrain response, although some effects have become evident in the last five years. These are expected to increase in magnitude and

---

*Two thaw slumps in Peel Plateau, NWT, activated since 1995 by an increasing frequency of heavy rain storms. These features are up to 1 km in width. They have developed in ice-rich ground that is remnant from the last glaciation.*

**INTENSE PRECIPITATION HAS TRIGGERED LARGE THAW SLUMPS**

CHRIS BURN teaches geography at Carleton University in Ottawa, Canada
Sweden

By JONAS ÅKERMAN

Sweden has permafrost only in the most northern parts of the country, at lower elevations in peatbogs and at elevations from 700 meters above sea level in the northernmost mountains. Since the early 1900s, there has been a long history of research on permafrost and the stability of palsas in the subarctic peat bogs from a geomorphological, ecological and climatological perspective. From very early on, the “borderline,” or very fragile permafrost in Sweden started to react to environmental changes caused by climatic change.

Monitoring of permafrost active layer depths began in 1978 at 10 sites in a 150 km east-west transect by the Lund Dept. of Physical Geography and Ecosystem Sciences. Last summer (2014) was very warm, especially in the degraded peat plateaus which directly affected the thicker active layer. The active layer data is submitted to the CALM (Circumpolar Active Layer Monitoring) database. In addition, ground temperatures from five boreholes have been downloaded and submitted to the GTN-P (Global Terrestrial Network for Permafrost) database. A snow manipulation experiment has also been running for 9 years in the same areas. In 2010, PAR (photosynthetically active radiation) sensors were added to the monitoring.

Increased photosynthesis compensates for a shorter growing season in subarctic tundra based on eight years of snow accumulation manipulations. Results showed higher PAR absorption (photosynthetically active radiation), together with almost 35% higher light use efficiency in treated plots (with added snow) compared to untreated plots. Estimations of Gross Primary Productivity suggested that the loss in early season photosynthesis, due to the shortening of the growing season in the treatment plots, was well compensated for by the increased absorption of PAR and higher light use efficiency throughout the whole growing seasons. This is most likely due to increased soil moisture and nutrients together with a shift in vegetation composition associated with the accelerated permafrost thaw in the treated plots.

The following projects deal partly with permafrost or problems in permafrost environments:

The aim of DEFROST (Depicting ecosystem-climate feedbacks from permafrost, snow and ice) is to understand how climate change induced changes in the cryosphere influence the ecosystem/geosphere processes which directly affect climate. We focus on key terrestrial, lacustrine and marine cryospheric components that have the potential for giving rise to substantial changes in climate feedback mechanisms both in terms of surface-atmosphere energy exchange and exchanges of greenhouse gases. DEFROST seeks to bridge existing gaps between climate modelling, cryospheric science, and Arctic ecosystem science.

ICOS – Integrated Carbon Observation System – is a European research infrastructure to quantify and understand the greenhouse gas balance of the European continent and of adjacent regions. ICOS Sweden is the Swedish contribution to this European effort and is a cooperation of several research institutes.

ICOS Carbon Portal offers access to research data from ICOS scientists all over Europe, as well as easily accessible and understandable science and education products. All measurement data available in the portal is quality controlled through the three thematic
centres, Ecosystem, Atmospheric and Ocean Thematic Centres and a Central Analytical laboratory.

LPJ-GUESS is a process-based dynamic vegetation-terrestrial ecosystem model designed for regional or global studies. Models of this kind are commonly known as dynamic global vegetation models (DGVMs). Given data on regional climate conditions and atmospheric carbon dioxide concentrations, it can predict structural, compositional and functional properties of the native ecosystems of major climate zones of the Earth.

LUCCI is a research centre at Lund University devoted to studies of the carbon cycle and how it interacts with the climate system. The centre involves about 120 researchers from four Lund University departments: Physical Geography and Ecosystem Science, Geology, Biology and Physics.

Norway

By BERND ETZELMÜLLE

The north Atlantic drift greatly influences the climate along the western coast of Norway, facilitating mild winters, cool summers and much precipitation despite the high latitudes. The Scandinavian mountain range stretches through most of the country from south to north, and acts as a barrier for the westerly winds, producing a strong climate gradient from the humid western parts to the drier and more continental eastern parts of Norway. Because of this climate setting, mountain permafrost is the dominating permafrost type. In southern Norway the lower permafrost limit decreases from about 1600 m in the west to around 1300 m above sea level (asl) in the east. In northern Norway, mountain permafrost prevails at above 900 m asl in the western coastal areas, and decreases down to around 400 m in the east in the county of Finnmark. There, much of the permafrost is associated to palsa and peat plateaus in mires, where organic layers and mosses protect ice lenses and ground ice from summer thaw. Such permafrost pockets ("sporadic permafrost") are even found close to sea level in Finnmark.

In Norway, the University of Oslo and the Meteorological Institute monitor ground temperatures in about 15 boreholes, between 10 m and 130 m depth. Data from these boreholes are stored in the Norwegian permafrost database NORPERM (http://geo.ngu.no/kart/permafrost/). These measurements show an increase of ground temperatures of up to 1°C since 1999, with permafrost clearly degrading in some of our study sites. Modelling exercises indicate permafrost covers around 6-8% of the land area, and has been warming and degrading since the end of the Little Ice Age c. 120 years ago. Along the lower limit of mountain permafrost and in the palsa areas, permafrost temperatures are just below 0°C and thus highly sensitive to climate warming.

Recently, the wetland areas of north-
ern Norway including the palsas and peat plateaus have gained increasing attention. First of all, detailed air photo and field surveys show ground ice has been reduced by up to 50% in many locations since the 1950s through thermo-karst processes, which adds up to a considerable permafrost loss. Secondly, this thaw may trigger an increased emission of greenhouse gasses from previously frozen, but now degrading organic material.

Most of the permafrost in Norway is situated in uninhabited areas, so that permafrost changes have limited impact on society. However, glaciations and glacier erosion have sculpted mountain areas in Norway, revealing many steep and unstable slopes. Many of those lie in the permafrost realm, and slope stability is influenced by permafrost and permafrost thaw. Large unstable mountain slopes, such as the continuously monitored Mt. Nordnes northeast of Tromsø, are most likely influenced by permanent ice in large cracks. Failure of this or similar slopes may affect roads and settlements, and in the worst case, trigger tsunamis if large rock masses hit fjords or lakes.

Finally, permafrost also has the capability to preserve objects as long as they are kept frozen. In the mountain permafrost areas of Norway we find a high abundance of ice patches, which are thin perennial ice accumulations frozen to underlying permafrost ground. The last decade’s climate warming has melted parts of these patches and revealed archaeological artefacts from historic and pre-historic human activity, such as reindeer hunting. Close to the highest mountain in Scandinavia, Galdhopiggen, many such artefacts are found. Here, an ice-tunnel was excavated 50 m into an ice patch, demonstrating that the ice and therefore the underlying permafrost are older than 6000 years (http://mimisbrunnr.no/?lang=en). This site is a laboratory for research and for visualising the impact of climate change to the public in the highly fragile mountain environments of Scandinavia.

View from Mt. Nordnes and instrumentation on an unstable, moving block above the fjord, view towards the Lyngen peninsula and the village of Lyngseidet.
The archipelago of Svalbard is located in the High Arctic around 78°N and 16°E, and has a maritime arctic climate, with mean annual air temperatures recently as warm as -3 to -4°C, and generally little precipitation. Clearly the climatology of the area is affected by the North Atlantic Drift bringing warm air into this high Arctic location. This special setting causes the permafrost in Svalbard to be the warmest this far north in the Arctic. In Svalbard permafrost is found outside the glaciated areas, which cover approximately 60% of the archipelago. The permafrost is continuous, meaning that it underlays typically 90-100% of the landscape. Permafrost is an important, but typically not directly visible, part of the cryosphere. Permafrost is often not directly visible in the landscape except for special landforms such as pingos, ice-wedge polygons and rock glaciers. All of these landforms are found in Svalbard, which has a high relief landscape, where permafrost is found both in the mountains and in the large valley lowlands.

Intensive studies of permafrost were only started in the 1990s in Scandinavia, whereas other parts of the Arctic have permafrost temperature data series dating back up to 30-40 years. This is due to other parts of the Arctic having much larger areas with permafrost. Svalbard, however, represents the only landscape in Scandinavia that has permafrost also in the lowland areas, where people are living directly on permafrost.

To be able to observe the permafrost thermal state boreholes have been drilled into the permafrost in different landforms. The first 102 m deep borehole at Janssonhaugen was drilled in 1998, and is the first deep permafrost borehole with thermal observation in the Nordic countries. Particularly since the International Polar Year 2007-2008 we now have more than 30 boreholes drilled into the permafrost for temperature observations in different landforms in Svalbard. The permafrost temperature varies between -3°C and -7°C. With the lowest temperatures found in the boreholes located high in the mountains, but also in boreholes in the sediment-in filled valleys. The highest temperatures are found along the west coast, where the influence from the North Atlantic Drift is largest.

The thickness of the important active layer on top of the permafrost is monitored in Svalbard as part of the Circumpolar Active Layer Monitoring Network (CALM) in the end of each summer, reaching its maximum thickness of between 74 and 110 cm over the last 15 years in fine-grained sediments in central Svalbard. In recent summers the thawing has been deeper.

Our permafrost temperature data from Svalbard is available in the Norwegian Permafrost Database, NORPERM (www.ngu.no/kart/permafrost_svalbard/?lang=English) hosted at the Geological Survey of Norway, just as some of the data is also now included into the Global Terrestrial Database on Permafrost (GTN-P) (www.gtnp.org).

As part of the research activities in the EU permafrost project, and in the Longyearbyen CO2 laboratory, we have collected the first deeper (10 to 60 m) cores from the permafrost in Svalbard. This allows us to study the content of ice and the ice types in the permafrost, and obtain more information on the age of the permafrost and the sediments in it. From this ongoing work we know that the permafrost in the large valleys is mainly formed during the last 5000 years, while permafrost in the mountains can be much older. This distribution is mainly due to the sea level having been higher after the last glaciation, and sedimentation in the large valleys following deglaciation so that most of the lowland permafrost in Svalbard is of Holocene age.
Iceland

By BERND ETZELMÜLLE

WITH ICELAND’S LOCATION in the middle of the Northern Atlantic Ocean, the island is dominated by mild and moist maritime weather conditions. Therefore, permafrost in Iceland is restricted to mountain areas, and mire areas in the high lying plateaus in the interior. The lower limit of mountain permafrost decreases from southeast to north in Iceland. We can expect widespread mountain permafrost above 1000 m above sea level (a.s.l.) in the south and 800 m a.s.l. in the north and the east of Iceland. The temperature within the mountain permafrost is comparably warm, only -0.5˚C to -1˚C below the freezing point. The snow cover governs the lower limit of mountain permafrost. A thick snow cover insulates the ground, while absence of snow due to wind redistribution of snow, for example, leads to more pronounced ground freezing. All these factors make mountain permafrost in Iceland highly vulnerable to climate change. Around these lower limits especially north of Vatnajökull and around most of Hofsjökull, palsa mires and peat plateaus are frequent. These mires contain pockets of ice lenses and ground ice, normally protected by thick organic layers and mosses. New observations indicate that these palsa and peat plateaus are also deteriorating. On Iceland the mountain permafrost zone covers an area of c. 8000 km² or around 8% of the land area, according to some simple modelling exercises.

Permafrost on Iceland is special because of Iceland’s location in the middle of the Mid-Atlantic rift zone with high volcanic activity. There is a high ground thermal heat flux, which keeps permafrost relatively thin. However, even on active volcanoes like Mount Hekla permafrost growth has been observed due to deposition of ash layers during winter which melt the snow-pack. Another landform indicative for mountain permafrost are rock glaciers, or creeping permafrost bodies along steep slopes. These forms are lobes of coarse, ice-cemented debris, where the ice slowly deforms and facilitate glacier-like movement. Hundreds of these rock glaciers can be observed particularly in Tröllaskagi in northern Iceland reveals the presence of mountain permafrost. The activity of these rock glaciers indicate whether they contain ice at present, or if they were formed during former and cooler climate conditions than today.

Finally, mountains often have steep slopes and rock walls, especially mountain ranges recently glaciated like most...
ranges in northern Europe. Glacier erosion steepens mountains slopes, and when de-glaciated they tend to become unstable and can fail. Permafrost stabilises steep slopes as water in crevasses and in sediments covering the slopes is frozen and therefore fixed. Thawing permafrost and melting ice in cracks and sediments favours instability, more frequent slope failures and greater impact on society and human activity. Recently, landslides were observed rapidly transporting frozen material downslope, indicating the failure of frozen bedrock and sediments. A warmer climate will certainly affect thaw of steep mountain slopes and the possibility of increased risk for slope failures in the future.

### Finland

By STEPHEN D. GURNEY and JUKKA KÄYHKÖ

**Measuring Over** 1000 km from south to north, the mean annual air temperature (maat) in Finland ranges from +5°C to -2°C. Unlike neighbouring Sweden and Norway, Finland is relatively low-lying, with only occasional summits reaching 1000 m elevation. These factors produce a ‘seasonal frost’ climate so that much of the country is not affected by permafrost. The northernmost regions of the country (the communes of Enontekiö, Inari and Utsjoki), however, have some areas of ‘sporadic’ permafrost – isolated pockets of permanently frozen ground underlying less than 30% of the ground surface.

Sporadic permafrost in Finland generally takes one of two forms. The first is found at higher elevations on the fells (‘tunturi’ in Finnish). In this case, the temperature of the bedrock some metres below the surface is continuously below 0°C. Loss of this type of permafrost will not necessarily result in land surface change or in the generation/release of greenhouse gases.

The second form of sporadic permafrost is found in the palsas mires (‘palsasuo’) of northernmost Finland. Palsas are mounds up to 7 m high with a frozen core, which grow in the thick peat of mires due to deep penetration of frost in winter, which does not thaw in the intervening summers (given the insulating effects of the overlying peat). In this setting, only the cores of the palsa mounds actually constitute permafrost and are surrounded by mire, which is only seasonally frozen. Should this type of permafrost be lost, land surface change and greenhouse gas production are likely to ensue.

Globally, areas of ‘warm’ permafrost are most vulnerable to decay. This ‘warm’ permafrost is typically sporadic, as discussed above. Since it is found in regions with a maat of between 1.0°C and -2.9°C, just a small shift in mean temperatures can lead to its loss. At present, the majority of permafrost in Finland is found only in Utsjoki and Enontekiö. Utsjoki is the most northerly region, but Enontekiö has, on average, higher elevations and hence the maat are similar, although snow cover differences also play a role.

The sporadic permafrost on the northern fells of Finland has a thickness of at least 50 m. The lower limit has been observed at an altitude of around 300 m in the Utsjoki region, but without geoelectrical soundings it is difficult to map. The active layer (the uppermost part which thaws each summer) above such permafrost is several metres thick. Some have speculated that this permafrost does not reflect the current climate. Further warming will certainly lead to the loss of this permanently frozen ground.

The sporadic permafrost in the frozen cores of the palsas is a rather special case. Here the permafrost occurs in a particular landform (the palsas) and the peat in which they develop. Palsas have a ‘life-cycle’ and decay when the layer of peat covering their frozen core becomes thin through stretching to accommodate the growth of the core and cracks open, leading to melting. When palsas collapse some of the peat decomposes, which produces greenhouse gases such as methane. With a warming climate there will be an increase in the number of decaying palsas and perhaps an absence of new palsas. This may form part of a positive feedback cycle, whereby warmer conditions lead to enhanced palsa decay, which in turn leads to greater greenhouse gas production.

Although permafrost degradation is a concern, other impacts of climate change on things such as winter snowfall (and hence the period of snow cover) may well have a much greater influence on the lives of people and the native fauna than thawing permafrost, at least in the short term.

---

The Circle 4.2015 17
PERMAFROST COVERS most parts of ice-free Greenland and holds organic matter which is decomposable upon thawing. But due to the young age of the ice-free part of Greenland the amount of stored carbon is limited. Taking into account the rate of decomposition, permafrost carbon in Greenland is unlikely to markedly affect atmospheric greenhouse gas levels in the near future. But investigations on permafrost stability and associated processes across the contrasting climates found in Greenland, is highly relevant in order to assess the importance of permafrost in the Arctic in general. This is the reason for the on-going research at at the Centre for permafrost (CENPERM) at University of Copenhagen.

The Greenland ice cap is such an efficient insulator against the cold of winter that the heat from the Earth prevents the formation of permafrost below the ice. Thus, permafrost is only found in ice-free areas and was formed in Greenland when the ice retreated from the coastal areas after the most recent ice age about 10,000 years ago. Since the last ice age, the majority of permafrost in Greenland has grown to a thickness of 10 m to more than 400 m. Near the rim of the ice cap, a recent retreat of the glacier ice is observed in several places, and new permafrost is formed. It is difficult to precisely measure the rate of permafrost thawing. One method is to measure the depth of the active layer. Yearly measurements of late summer maximum thaw depth by the Circumpolar Active Layer Monitoring research network (CALM) include few Greenlandic sites. CALM Measurements in Zackenberg, Northeast Greenland in 1996 show an increase in the maximum active layer depth of more than 1 cm per year and reveal a faster increase on dry tundra and a slower increase in wet fens. The ice content is crucial to the future thaw rate and to the environmental impact of the thawing permafrost. Mathematical modeling is also used to predict current and future thawing of permafrost. Uncertainties are linked to these models, since the models only to a certain extent take into account draining, erosion, deposition and geomorphology of the landscape. Presently, the models suggest that permafrost temperatures in Zackenberg 10 m below the soil surface have been between -7 and -8 °C within the last 100 years, and that the temperatures have risen to the actual -6 to -8 °C and show a potential increase to between -2 and -3 °C before year 2100. Furthermore, based on the thermal properties of the active layer and of the permafrost combined with a projection of temperatures and precipitation, a water and energy budget is calculated. The COUP model (Coupled heat and mass transfer model for soil plant-atmosphere systems) has been calibrated and afterwards validated on data series from both Western and Eastern Greenland, and recently used for a sensitivity analysis. In Zackenberg the sensitivity analysis shows that the maximum active layer depth will increase and that 20-70 cm of the upper permafrost will potentially thaw before year 2100. Moreover, the sensitivity analyses show that the ice content of the permafrost and the future volume and distribution of snow in the landscape are crucial inputs to provide more robust projection of future thawing.

NEAR THE RIM OF THE ICE CAP, A RECENT RETREAT OF THE GLACIER ICE IS OBSERVED IN SEVERAL PLACES

The upper ice-rich permafrost in Greenland is exposed and the composition of sediments, water and air bubbles is clearly seen. The last component, microorganisms, is not visible, but crucial to the understanding of the consequences of the thawing permafrost. The picture shows a landscape strongly influenced by permafrost thawing followed by collapse in Zackenberg in Northeast Greenland.

BO ELBERLING is a Professor & Director of the Center for Permafrost (CENPERM) at University of Copenhagen.

The upper ice-rich permafrost in Greenland is exposed and the composition of sediments, water and air bubbles is clearly seen. The last component, microorganisms, is not visible, but crucial to the understanding of the consequences of the thawing permafrost. The picture shows a landscape strongly influenced by permafrost thawing followed by collapse in Zackenberg in Northeast Greenland.
IN THE UNITED STATES, permafrost is present in Alaska as well as the higher altitudes of the Rocky Mountains, the Cascade Range, Sierra Nevada, as well as Hawaii. We confirmed presence of permafrost at the Mauna Kea (4205m) summit area but none at Mauna Loa (4169m) volcanoes. There are several ice caves observed at Mauna Loa but no permafrost due to smooth mountain slopes, much different micro topography than Mauna Kea and also its recent eruption history in 1984.

Permafrost extends widely across most of Alaska except in the Aleutian Islands and along the Gulf of Alaska. Permafrost conditions vary depending on location. Over the last 20 years, permafrost temperatures in Alaska have changed noticeably. Generally, the increases in permafrost temperature are more pronounced at coastal Arctic sites (from 1.5 to 3.0°C at the permafrost table) and less pronounced in Interior Alaska (from 0.5 to 1.5°C). Continuous and colder permafrost (-3°C and lower) is mainly found on the North Slope (Barrow; Kaktovik, -9°C) and in the Brooks Range (Arctic Village, -3.8°C). Southwest of the Brooks Range, permafrost is discontinuous. Typical alluvium or glaciofluvial coarse sediments are absent of permafrost. Many native villages, such as in the Kobuk and Koyukuk River valleys, are located on permafrost-free terrain (Ambler, Kobuk, or Huslia, 0 to 5°C). The Seward Peninsula and Bering Strait coastal regions have a maritime climate and a variety of permafrost conditions. Permafrost temperature is between -3°C (Kotzebue, Shishmaref, Wales) and -2°C (Teller, Nome). There is an absence of permafrost (slightly above 0°C) on the south side of the Seward Peninsula (Elim, White Mountain). Storm surge and spring river-flooding events heavily influence permafrost distribution in the Yukon-Kuskokwim Delta. Permafrost is absent in lower flooded terrain such as Nunam Iqua (Sheldon Point), Scammon Bay, Hooper Bay, Emmonak, Kotlik, and Chefornak. However, in villages located in higher (older) terrain (20–50 cm higher than flooded terrain), there is permafrost, with a temperature range between -0.8 and -0.2°C.

The distribution of permafrost in Bering Sea islands is exceptional. There is well-developed permafrost found on St. Lawrence Island and Little Diomede Island (-2°C). Permafrost appears in eolian sediments at Nunivak Island and Nelson Island (-0.3°C). Permafrost is absent in the Pribilof Islands. Volcanic activity on Saint Paul Island created several lava tube caves. Ice has not been recorded in any of the caves.

In the greater part of Interior Alaska and the Copper River Basin, permafrost is present discontinuously. For example, ground temperature may fluctuate between -2 to 2°C over a 1 sq. km area. South-facing slopes do not contain permafrost (0 to 2°C), unlike north-facing slopes and valley bottoms, which do (-3 to 0°C). Permafrost distribution is strongly affected by solar radiation (slope aspect) and soil properties.

The southern boundary of permafrost in Alaska is around 60°N latitude, but it is an irregular boundary. In the Bristol Bay area, glaciofluvial and glacial history prevented the formation of permafrost, but permafrost developed in eolian sediments (Eek, Koliganek, Quinhagak) slightly below 0°C to -0.2°C. In the Gulf of Alaska region, permafrost is absent due to heavy snowfall and warm ocean temperatures during winter, such as in Valdez (4°C). However, in some of the peat-rich marshy areas near Anchorage, ice-rich silty sediments remain frozen (-0.2°C).
Shifting sands – living on permafrost

By BRONWYN BENKERT

In the North, we live on permafrost. Much of our infrastructure is built on ground that is at or below 0°C for two years or more. We travel across permafrost, and it supports our homes and workplaces. Northerners have long had to contend with permafrost in construction and economic development – in the Klondike gold fields, prospectors at the turn of the 20th century actively thawed frozen ground to reach pay dirt, while workers constructing the Alaska Highway during the Second World War battled thawing ground that never stabilized, forcing on-the-fly adaptation of construction processes.

Northerners continue to adapt to our permafrost environment, which forces us to use ingenuity and innovation as we invest in and maintain infrastructure on permafrost. This task has become increasingly challenging, as a result of compounding factors that include heightened development intensity and a changing climate. The goal of preserving costly northern infrastructure prompts us to develop a thorough understanding of permafrost characteristics and its dynamic responses to anthropogenic and environmental stressors. In Yukon, research focuses on identifying solutions to permafrost thaw impacts on infrastructure. As the only dedicated permafrost research group in northern Canada, the Northern Climate ExChange (NCE), part of the Yukon Research Centre at Yukon College, is working with community, government and industry partners to assess permafrost vulnerability to thaw, and to identify suitable measures to keep it stable.

Yukoners have regularly witnessed impacts of permafrost thaw on infrastructure. In January 2015, a 15-year-old Yukon school was closed due to concerns about its structural integrity. Shifts in the foundation were attributed, at least in part, to permafrost thaw under the building. Substantial investment was required to repair the building before it could be re-opened in September. Prior to the closure of the school, NCE partnered with Yukon government to assess permafrost conditions and recommend practices that could be used to slow or prevent thaw. These ranged from modified snow clearing practices to engineering solutions. Permafrost cores, ground temperature records and geophysics profiles were collected and analyzed by NCE researchers. Together, these approaches form the basis of our understanding of conditions that contributed to infrastructure vulnerability and damage, and may contribute to the preservation and longevity of our buildings.

Increasingly, permafrost-related information is being integrated as part of the planning process for local development. In Yukon, many communities...
are proactively adopting adaptive planning approaches, based in part on landscape hazard maps the NCE and its partners have developed. These maps integrate current and future hazards associated with permafrost, surficial geology and hydrology into easy-to-interpret, community-scale maps. The hazard risk maps have assisted Yukon communities and other agencies in choosing suitable locations for new infrastructure by helping them avoid key thaw-sensitive areas, and by allowing them to assess the suitability of development projects for local conditions.

In some cases, choosing stable or non-permafrost locations for infrastructure is impractical. Twenty-five percent of Yukon’s 4800 km highway network is built on permafrost. The maintenance of these sections can cost in excess of 5 times that of non-permafrost sections.

Where permafrost is already degrading, the management of nearby water and on-going remediation are continually required to reduce infrastructure deterioration. Further, sections of highway overlying permafrost that are currently stable may be affected by future permafrost degradation – it is likely that permafrost impacts on linear infrastructure will become more significant with time.

Fortunately, modified construction practices and thaw mitigation techniques can be used to preserve permafrost and reduce degradation impacts on linear infrastructure like highways.
The tipping point

Permafrost carbon feedback represents a very slow, but irreversible climatic tipping point. Permafrost will thaw slowly over many years, but once it thaws, you cannot refreeze it, writes KEVIN SCHAEFER.

PERMAFROST is perennally frozen ground remaining at or below 0°C for at least two consecutive years. Regions with extensive permafrost occupy about 24% of the land area in the Northern Hemisphere. The active layer is the surface layer of soil above the permafrost that thaws each summer and refreezes each winter. The thickness of the permafrost layer depends upon a delicate balance between freezing from surface due to cold winter temperatures and warming from the Earth’s molten interior. Permafrost is thickest along the Arctic coastline where temperatures are coldest, extending down to depths as great as 1500 meters. Air temperatures increase southward from the Arctic Ocean and the thickness of the permafrost layer becomes progressively thinner, eventually disappearing altogether at latitudes between 50 and 60 degrees north.

The effects of warming temperatures due to global climate change have begun to thaw the permafrost. The effects of climate change are especially strong north of the Arctic Circle, where the warming rate is roughly double the global average. The rising temperatures have caused permafrost to disappear entirely in some regions, moving the southern boundary of the permafrost domain northward. The active layer thaws deeper each year as summer temperatures rise. The temperatures within the permafrost layer itself remain below freezing, but are rising at rates as high as 1°C per decade. These current temperature increases are truly alarming considering that permafrost can take hundreds of years to respond to variations in climate such as the little ice age 400 years ago.

Buildings, roads, and other infrastructure will be damaged or destroyed as permafrost continues to thaw. Ice within permafrost binds soil particles together like cement. Permafrost is hard, dense, and erosion resistant, but if the permafrost thaws, the ice turns to water and the permafrost turns to mud, destabilizing and collapsing buildings with remarkable rapidity. Retreating sea ice has increased wave intensity, resulting in rapid coastal erosion. Indeed, several villages have already been moved because the coast has simply eroded away.

Climate change is affecting permafrost, but thawing permafrost will also affect the global climate. Organic matter frozen in permafrost contains enough carbon to easily double the carbon dioxide concentration in the atmosphere. Since the end of the last ice age about 15,000 years ago, this frozen carbon was buried by sedimentation and other processes. The soil depth increased as sediment built up, but the surface thaw depth stayed constant such that organic
matter at the bottom of the active layer became frozen into the permafrost. The organic matter will remain stable as long as the permafrost remains frozen, but, like broccoli removed from a freezer, once the organic matter thaws it will decay and release carbon dioxide and methane into the atmosphere. Once released into the atmosphere, this carbon dioxide and methane will amplify warming due to the burning of fossil fuels in a process called the permafrost carbon feedback.

For the ‘business as usual’ scenario where we continue to burn fossil fuels at current rates or higher, thawing permafrost will release ~120 gigatons of carbon by 2100 with a total of ~240 gigatons by 2300 resulting in a global temperature increase of ~0.6 degrees centigrade. The permafrost carbon feedback will complicate the negotiation of the climate change treaty. The international community is currently negotiating a treaty to stop global climate change based on a target of 2 degrees centigrade global warming above pre-industrial levels. If we reduce fossil fuel emissions to hit the 2 degree centigrade warming target, the rate of permafrost thaw and associated emissions will go down to ~60 gigatons by 2100 with an additional global warming of ~0.1 degrees. Again, half of the emissions will occur after 2100 with a total of ~120 gigatons by 2300 resulting in a global temperature increase of ~0.2 degrees centigrade. While this is small compared to fossil fuel emissions, if the international climate change treaty does not account for emissions from thawing permafrost, we will overshoot our 2 degree warming target.

The permafrost carbon feedback represents a very slow, but irreversible climatic tipping point. Permafrost will thaw slowly over many years, but once it thaws, you cannot refreeze it. The decay of the thawed organic matter occurs slowly over hundreds of years because the Arctic soils will still be fairly cold and wet. However, once the organic matter decays away, there is no way on human time scales to put it back in the permafrost. In essence, once the permafrost carbon feedback starts, it will persist for centuries.

Kevin Schaefer is a research scientist at the National Snow and Ice Data Center (NSIDC), University of Colorado.
Firefighters perform burn out operation in shaded fuelbreak

The impact of forest fires

Left: A severely burnt area in the southern Northwest Territories, Canada, where the vegetation has been completely consumed, showing the bare mineral soil and allowing more heat to transfer into the ground. Right: An unburnt area nearby where the organic material is thick and insulates the permafrost below.
Climate change is one of the most substantial and widespread environmental phenomena of our immediate future, with the effects of global climate change projected to be most severe at high latitudes. Permafrost landscapes make up a large portion of the Northern hemisphere. **Jean Holloway** says understanding the impacts of change for the people, ecosystems and infrastructure in these areas is important.

**There has been** substantial winter and spring warming in west-central and northwestern Canada and virtually all of Siberia over the past three decades. How permafrost is affected by these temperature changes depends on complex interactions among topography, surface water, soil, vegetation, and snow, which vary greatly between sites, even over short distances. Vegetation, in particular, can insulate permafrost from the atmosphere, making it resilient to increases in air temperature, at least in the short term. This ecosystem-protected permafrost covers millions of square kilometres worldwide and is particularly sensitive to climate and environmental change as it is just below 0°C, thin and usually cannot be re-established after disturbance. The most widespread source of disturbance of this permafrost is forest fire.

Forest fires are a natural and essential part of the boreal forest ecosystem, and typically locations burn every 50-300 years. Global warming and greater human activities have increased the frequency and magnitude of forest fires, which generally occur in warm and dry summers. The number of recorded forest fires in Canada has increased substantially in the last 30 years. In Siberia 1.5% of the total forested area burns annually. The response of permafrost to forest fires depends on the degree to which the permafrost is protected by the ecosystem.

**Jean Holloway** is a PhD candidate in the Dept. of Geography at Ottawa University focusing on the impacts of forest fires on permafrost in the southern Northwest Territories, Canada.

Landslides following forest fire in the Mackenzie Valley. The rapid thaw of permafrost led to ground ice melt and loss of strength.
The heat from the fire itself does not directly affect permafrost. The damage occurs when intense fires destroy the organic layer that is insulating the ground. This exposes the underlying mineral soil, which is more conductive than the surface organic mat, and allows more heat to get into the ground. Similarly, fire removes trees, which catch snow thus creating a deeper layer of snow that shields the ground from necessary cold winter temperatures. The active layer deepens until the upper layers of permafrost begin to thaw. Other factors that aid in this degradation include decreasing albedo due to surface darkening, and loss of shading from the tree canopy. Soils with permafrost in the coldest and wettest landscape positions (e.g. valleys) usually do not thaw as deeply after fires as soils in warmer and drier positions, such as hilltops or south-facing slopes. Fire severity is also significant, especially the degree to which the ground surface layer is burned. Complete destruction of the forest and the surface organic layer by hot, slow-moving fires will have the greatest impact, while fast-moving fires may skip over patches of forest, and low intensity fires can leave much of the organic layer intact. While the general influence on permafrost is therefore clear, how it will respond at a particular site depends on numerous local factors.

Thaw and degradation of burned areas is expected to continue until sufficient re-vegetation occurs to re-establish the insulating organic mat. Vegetation recovery after forest fires has a major influence on stabilization of permafrost thaw. Growth is rapid in the first few years, and then slows down with time, as there is more competition for moisture and sunlight. The complete recovery of the ecosystem to pre-burn conditions can take up to 50 years. However, this depends on the climate still being suitable for permafrost. If the permafrost is ecosystem-protected and the climate is warming, permafrost degradation may continue until it disappears entirely.

Forest fires also affect permafrost landscapes in ways that are more noticeable. In the first and second years after a fire, landslides can occur on hill-slopes. Progressive uneven surface subsidence of the ground (called thermokarst) may also occur for years because of melting ground ice within the permafrost. This can affect current infrastructure as well as future development, especially as the frequency of fire means that many developments in the boreal forest may expect to be affected by fire at some point during the lifespan of infrastructure.

Another important effect of forest fires is carbon release during the fires and from thaw of permafrost post-fire. Boreal permafrost soils store large amounts of organic carbon, and fire disturbance influences the amount and type of carbon in the soil. Forest fires release approximately 53 million tonnes of carbon from North American boreal forests each year. Vegetation re-growth post-fire actually ends up storing large amounts of carbon, but in a warming climate with a higher frequency and magnitude of forest fires, this is expected to change. Furthermore, thaw of permafrost following forest fires allows carbon that has been trapped in frozen soils to become available for decomposition by soil microbes. Both these phenomena create a positive-feedback loop: climate change results in a greater frequency and magnitude of forest fires, which release greenhouse gases into the atmosphere, which results in more climate change, and so on.

How permafrost responds to forest fire is a complex issue, but it is clear that a warming climate and the expected increase in the frequency and magnitude of fires will have a substantial impact on permafrost thaw and degradation, especially in the discontinuous zone. It is important that we understand these impacts so we can make informed decisions on fire-management and how to deal with post-fire issues such as landslides and positive feedback adding to climate change. ☞

Due to global warming, permafrost is degrading around the world and China is no exception. Permafrost regions occupy 2,150,000 km² or roughly 22% of China. Most of this is on the Qinghai-Tibet Plateau, also known as the Third Pole. More than half of the land area of the Qinghai-Tibet Plateau is underlain by permafrost, which is the highest and most extensive high altitude permafrost on Earth. Fujun Niu says building on this plateau has required innovative solutions.

The Qianghai-Tibet Plateau is characterized by high ground temperature (warm permafrost), along with high ice content. The fragile ecological environment on the plateau makes the permafrost highly sensitive to climate change and human activities. Data indicates that a large portion of the Qinghai-Tibet Plateau has experienced significant warming since the mid-1950s, with rapid permafrost degradation. Evidence includes increased mean annual ground temperature (MAGT), increased active layer thickness, talik development, and even disappearance of permafrost islands. Data show that the thickness of the active layer has increased by 0.15 to 0.50 m and ground temperature at a depth of 6 m has risen by about 0.1° to 0.3°C between 1996 and 2001. Made worse by human activities, the degradation has been seriously compromising the engineering stability of local infrastructures.

The Qianghai-Tibet Highway, con-
permafrost in the “Third Pole”

The duct-ventilated embankment with the slopes covered by crushed-rock has an obvious effect of cooling down the subgrade.

structed in the 1950s on the plateau, was the first large scale infrastructure in the permafrost regions. The permafrost was ignored during the highway construction with many subsequent settling problems. Investigations indicated that approximately 85% of the damage to highway embankments was caused by the thaw settlement of ice-rich permafrost. In the Qinghai-Tibet Engineering Corridor, over one half of the permafrost is ‘warm’ and approximately 40% ice-rich. Considering the permafrost scenarios influenced by local natural factors, permafrost degradation and lessons from the other existing infrastructures, the traditional passive method of simply increasing the thermal resistance by raising the embankment height and using insulating materials has been proven ineffective in warm and ice-rich permafrost areas. Thus the Qinghai-Tibet Railway was designed and constructed using a ‘cooling roadbed’. This method cools the roadbed by lowering the ground temperature. Construction of the railway began in 2001 and was completed in 2006 using a number of measures to adjust and control the amount of solar radiation, heat convection, and heat conduction to cool the roadbed for the railway. Various engineering measures, including crushed rock embankment, duct-ventilated embankment, sun-shading embankment and thermosyphon embankment, were also tested and applied.

The crushed rock embankment has since been widely adopted. A decade of ground temperature data indicates that the thermal regime within and beneath the embankments varied significantly with embankment structures. Obvious asymmetries, which might cause longitudinal cracks, existed in the permafrost table and ground temperature field of the traditional embankment and the crushed-rock basement embankment. The ground temperatures, especially under the sunny slopes, increased gradually even though the permafrost table was elevated, indicating that the thermal regimes of the traditional embankment and crushed rock bed embankment were disadvantageous for their thermal stabilities. In contrast, the ground temperature fields of both the crushed-rock sloped embankment and the U-shaped crushed-rock embankment remained symmetrical, and their permafrost tables were also raised and then maintained.

The U-shaped crushed-rock embankment has the best long-term effect in both decreasing the ground temperature and improving the symmetry of the temperature field. Cooling roadbed methods, therefore, are long-term effective, guaranteed for train speeds of 100 km/h.

The ecological environment of the plateau is very vulnerable. Studies on the impact of the Qinghai-Tibet Railway showed that accommodation, followed by shopping and food service, accounts for the highest percentage of the ecological footprint caused by passenger transport. Carrying capacity brought by freight transport is increasing year by year and accounts for 51% of the total ecological footprint on Tibet.

FUJUN NIU is Vice-director of the State Key Laboratory of Frozen Soils Engineering

PERMAFROST WAS IGNORED DURING HIGHWAY CONSTRUCTION WITH MANY SUBSEQUENT PROBLEMS

The Circle 4.2015 27
Fissures of Men

A longitudinal crack due to permafrost degradation along the Alaska Highway, Yukon.

Why we are here
To stop the degradation of the planet’s natural environment and to build a future in which humans live in harmony with nature.

www.panda.org/arctic