PAGE21

Changing Permafrost in the Arctic and its Global Effects in the 21st Century

SEVENTH FRAMEWORK PROGRAMME

Preface

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During the past few decades climate change has become the major environmental issue of our time. Not only scientists, but also the general public and the politicians that represent them, are increasingly faced with the effects of climate change on our planet. Observations show that the impacts of climate change are felt more rapidly in the Arctic than over the rest of the globe. Initially, it was the melting polar ice sheets and the retreat of the sea ice in the Arctic Ocean that captured the most interest, but now the thawing of the permafrost layer is also seen as an increasingly important issue, with serious consequences on climate feedbacks. Today, climate warming and the consequent reactivation of the immense currently frozen carbon reservoir in the permafrost, have become one of the main topics in climate research.

Traditionally in Europe, permafrost research mostly concentrated on mountainous areas. The increasing interest in global warming, however, has resulted in geographically broader EU-funded initiatives, of which the latest is the PAGE21 project. PAGE21, "Changing permafrost in the Arctic and its Global Effects in the 21st Century" brought together all major European permafrost research institutes as well as leading North American and Asian permafrost research groups. This grouping makes the project one of the first truly circumpolar permafrost research initiatives.

The project adopted an inter-disciplinary approach towards data collection and analyses, combining field measurements with remotely sensed satellite data and global climate models. The output from the analyses helps us to advance understanding of permafrost processes at multiple scales, resulting in improvements in global climate modelling and the ensuing future climate projections.

It has been a great pleasure to lead this research consortium and I am very proud of the advancement the project has been able to make in permafrost, and more broadly, in climate science. The rapid changes that are occurring in the Arctic require a flexible and responsive research community. I believe that PAGE21 is an excellent example of the dynamic approach needed to respond to the developing research agenda in European permafrost research.

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Summary

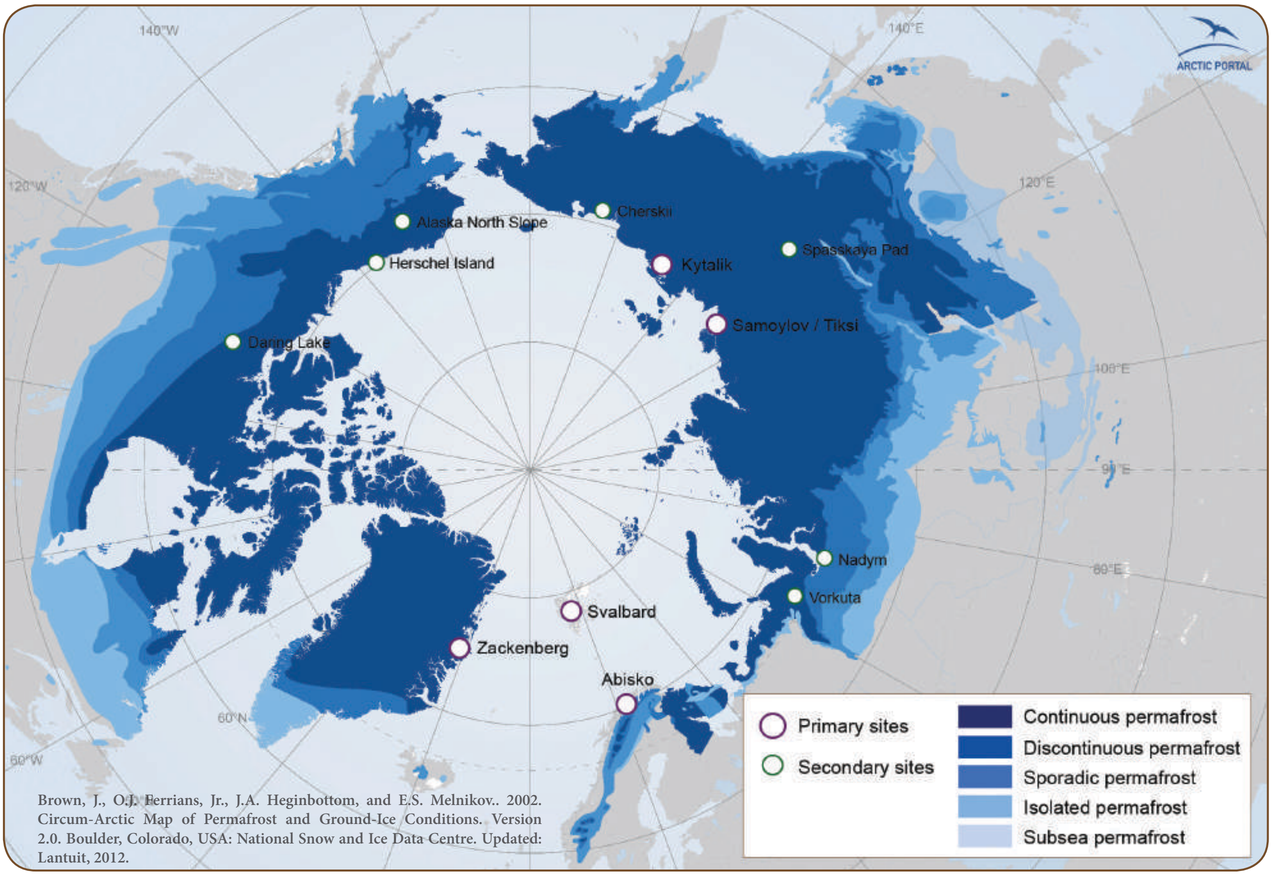
Extensive research shows that the Arctic's climate is warming at an unprecedented rate. The consensus view is that this warming is due to anthropogenic greenhouse gas emissions to the atmosphere. Even if global greenhouse gas emissions were to be cut to zero by 2100, the temperature in the Arctic would still rise more than 2 °C relative to the present-day. Since the early 1980s, the warming Arctic climate has led to increasing permafrost temperatures in most regions. This warming has caused a permafrost thaw, which releases previously frozen greenhouse gases in to the atmosphere. This so-called "permafrost-carbon- feedback" process is expected to accelerate climate change on a global scale.

The project "*Changing permafrost in the Arctic and its Global Effects in the 21st Century*", PAGE21, was designed to broaden the physical knowledge base on permafrost processes and to include processes affecting the permafrost-carbon- feedback into the land-surface modules of the three major European global climate models. Using these improved models, PAGE21 has shown that by 2100 the total amount of carbon released into the atmosphere from thawing permafrost is at the lower end of the previous IPCC AR5 estimates, those being between 50 to 250 Gt C. However, in the expected much warmer world, the permafrost loss will continue for centuries, as the previously frozen Arctic ecosystems degrade and release large amounts of carbon previously locked into frozen permafrost soil.

Permafrost and Climate Change

Permafrost is defined as ground that remains at or below 0 °C for at least two consecutive years. It occupies up to 24% (23 million km2) of the land in the northern hemisphere. Most of the permafrost existing today was formed during cold glacial periods, and has persisted through a warmer interglacial period for the past 10 000 years.

Permafrost – perennially frozen ground.



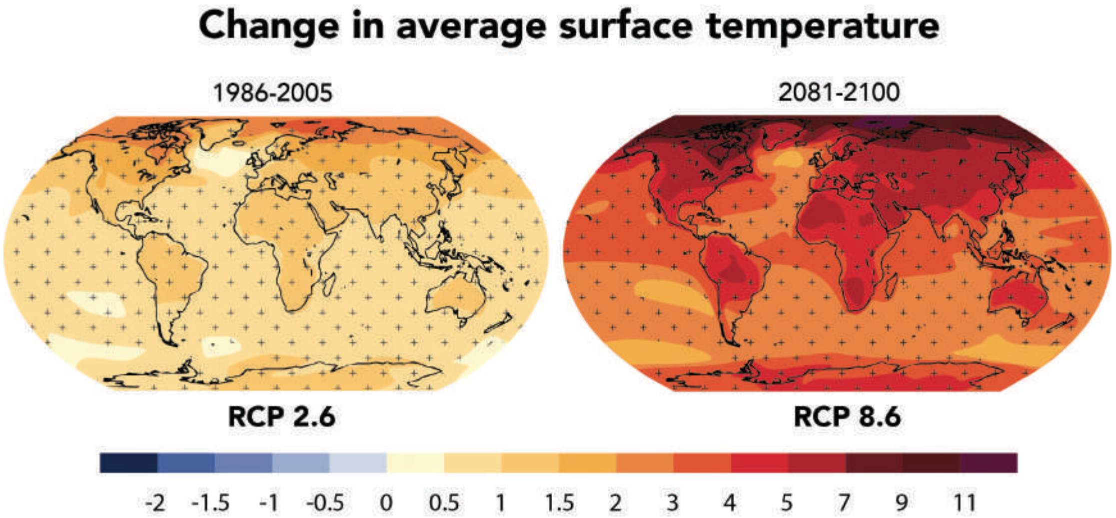
Brown, J., O.J. Ferrians, Jr., J.A. Heginbottom, and E.S. Melnikov.. 2002. Circum-Arctic Map of Permafrost and Ground-Ice Conditions. Version 2.0. Boulder, Colorado, USA: National Snow and Ice Data Centre. Updated: Lantuit, 2012.

The latest Assessment Report of the International Panel on Climate Change (IPCC, 2014) concludes that the Earth's mean surface temperature is projected to rise over the 21st century under all greenhouse gas emission scenarios. For the "business-as-usual" scenario (the RCP8.5) where emissions continue to grow over the 21st century, nearly tripling by 2100, climate models simulate a global warming of about 3.7 °C by the end of the century, compared to today's level.

Because of feedbacks in the climate system, such as reduced snow and sea-ice cover, this warming is predicted to be much larger at high latitudes. For the same "business-as-usual" (the RCP8.5) scenario, climate models have predicted a warming of about 8.3 °C by the end of the 21st century for the Arctic region (67.5°N to 90°N) – more than double the global average warming.

Arctic amplification of global warming.

Even for the very extensive mitigation scenario (called RCP2.6) where global emissions of greenhouse gases are near-zero by the end of the century, global warming is still about 1°C relative to the present-day, with the Arctic region showing a temperature increase of double that, at around 2.2 °C.

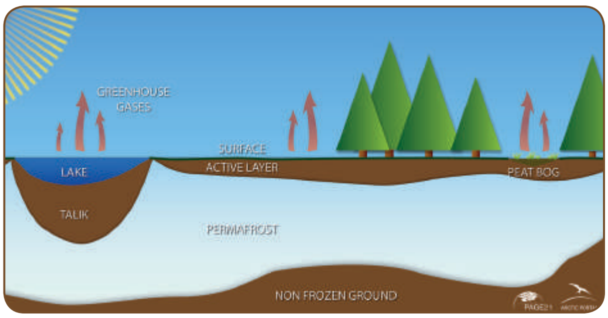


From IPCC, 2014: Climate Change 2014: Synthesis Report

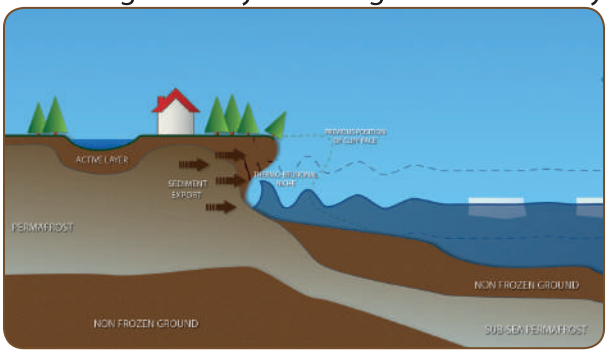
The marked difference between Arctic warming and global warming is especially important because Arctic warming has the potential to unleash the vast amount of organic carbon currently frozen-in to permafrost soil. This carbon constitutes approximately 50% of the estimated global total of belowground organic carbon and is twice as much as that contained in the Earth's atmosphere.

Permafrost deposits contain vast, currently frozen, reservoirs of organic matter, which may form greenhouse gases.

The sheer size of the permafrost carbon pool, together with the magnitude of predicted Arctic climate change suggests that destabilizing this carbon reservoir is likely to create a major global-scale feedback. Indeed, a destabilization of just 10% of the permafrost carbon, and its subsequent emission as carbon dioxide, could induce additional costs of 350 trillion Euros per year for the European Economy (Stern, 2006).
Until recently, we understood very little about the physical and biogeochemical processes at play in permafrost. Major knowledge gaps have hampered accurate assessment of the vulnerability of Arctic permafrost to climate change, and the implications of permafrost thaw on future greenhouse gas (GHG) emissions.



The PAGE21 project has broadened this knowledge base by assessing the vulnerability



of Arctic permafrost to climate change and by reducing the uncertainties in permafrost-related feedbacks to the global climate. In particular, PAGE21 has:

- *Identified the key physical processes controlling the vulnerability of the carbon and nitrogen pools in Arctic permafrost to future climate change.*

- *Quantified the effect that the permafrost-related Arctic climate change feedback will have on anthropogenic global warming.*

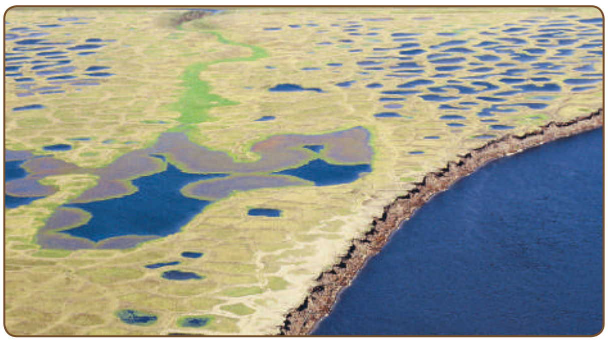
Permafrost is warming everywhere

The global climate is characterized using Essential Climate Variables (ECVs). These ECVs were established by the Global Climate Observing System (GCOS) and the World Meteorological Organization (WMO) and are monitored by international networks. The Global Terrestrial Network for Permafrost (GTN-P) is one of these networks.

An Essential Climate Variable (ECV) is a physical, chemical, or biological variable that critically contributes to the characterization of Earth's climate.

Since the 1990s The Global Terrestrial Network for Permafrost (GTN-P) has been collecting data on the permafrost ECV – permafrost ground temperature and active layer thickness – aiming to obtain comprehensive observational evidence of the spatial structure, trends and variability of permafrost change.

Since the early 1980s, the warming climate has increased permafrost temperatures in most Arctic regions. The latest measurements suggest that permafrost temperatures have increased by between 0.5 °C and 2 °C in the time period leading up to PAGE21.



In order to give a better overview of permafrost warming and to enable visual representation of the temperature trends, PAGE21 designed a comprehensive database for the GTN-P. This PAGE21/GTN-P Data Management System

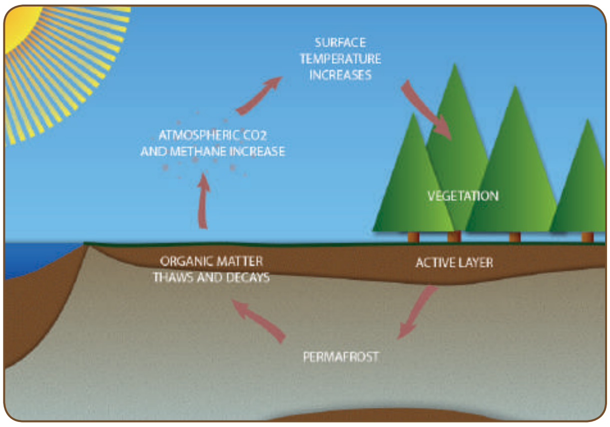
(DMS) now stores data on the permafrost Essential Climate Variable in standardized format. This data can now act as an "early warning system" for the impacts of climate change in permafrost regions.

New PAGE21 / GTN-P Data Management System for permafrost Essential Climate Variable. www.gtnp.org

The DMS also enables analyses on the effectiveness of the spatial distribution of permafrost measurement sites, providing valuable statistical information on the current gaps in monitoring networks. First results of this type of analysis show that more permafrost measurement sites are located in areas with low rates of expected temperature rise; the number of sites within Arctic areas, where climate models project the greatest temperature increase, is relatively low.

The data stored in the DMS is freely available, not only to scientists, but also to politicians, decision-makers and other interested parties. Every two years, the GTN-P will prepare a report on the state of the permafrost, based on the latest data, providing up-to-date information on temperature and active layer changes.

Permafrost carbon, the sleeping giant



As the Earth's climate warms, the permafrost thaws. Organic material previously frozen in permafrost then starts to decompose and releases greenhouse gases into the atmosphere. These greenhouse gases in turn amplify the warming and further increase the Earth's surface temperature, creating a self-sustaining cycle of climate warming. This so-called "permafrost-carbon-feedback" is expected to impact climate change on a global scale.

Permafrost-carbon-feedback is the cycle in which currently frozen carbon is released to the atmosphere due to a warming climate, which in turn further increases global warming.

The strength of the permafrost-carbon-feedback depends on the amount of organic carbon present in permafrost soils and its vulnerability to decomposition following permafrost thaw. Knowing both the size and the vulnerability of the permafrost carbon pool are essential if we are to predict the magnitude and timing of the future release of greenhouse gases from thawing permafrost.

The latest research shows that the Arctic permafrost carbon pool contains ca. 1300–1600 Pg carbon, (1 Pg = 1 billion tonnes). This is approximately 50% of the total global belowground organic carbon pool and twice as much as all the CO_2 in the Earth's atmosphere.

Approximately 50% of the estimated global total of belowground organic carbon is locked into permafrost.

The rate at which the organic carbon in permafrost soil decomposes varies greatly depending on factors such as soil age, depth and type. The rate of decomposition generally decreases with both age and depth. However, soil properties vary greatly across a range of scales, from the plot to the landscape and this variability makes the preparation of accurate maps of permafrost-related soil properties problematic.

An analysis of unique compilations of large datasets, however, reveals that the vulnerability of permafrost carbon is highest in soils deposited by rivers and then decreases for wind-blown soils, and other upland mineral soils. The lowest vulnerability is observed in peat deposits.

Although climate models include many of the essential land-ecosystem processes, the permafrost–carbon-feedback was not represented in the global climate models used to project the future climate for the IPCC AR5 or for the COP21 negotiations. For example, the IPCC AR5 "business-as-usual" (RCP8.5) and the extensive mitigation (RCP2.6) scenarios only account for the greenhouse gas sources anticipated under the current emission regime and thus do not include the added warming from the permafrost-carbon-feedback.

Many permafrost-related processes were lacking in the global climate models informing the IPCC AR5 and COP21 negotiations.

Permafrost warming impacts the Earth's climate

One of the major achievements of PAGE21 was to incorporate the most important permafrost-related physical processes into the land-surface modules of the three major European global climate models used to inform the IPCC Assessment Reports.

Results from these PAGE21-improved models show notably less permafrost loss for the RCP8.5 scenario than those models used for IPCC AR5. The models used for AR5 calculated an average 81% loss of near-surface permafrost by 2100. In contrast, the PAGE21-improved models calculated an average loss up to 75%. The main reason for the lower estimates by the improved models is the inclusion of key processes, such as moss and snow insulation, the inclusion of organic soil, and better representation of the deep soil dynamics. All these factors tend to weaken the propagation of warming from the surface to greater depth, which reduces soil thawing. Nevertheless, PAGE21 still simulated the shrinking of near-surface permafrost areas at a rate of about 0.5 million km2 per decade. This rate implies that if warming continues, as assumed by RCP8.5, the entire permafrost zone will thaw over the next several centuries.

PAGE21-improved European global climate models show up to 75% reduction of permafrost extent by 2100 for the business-as-usual (the RCP8.5) scenario.

Simulations made with the PAGE21-improved models on the increase in atmospheric CO2 show similar results. Starting from an initial stock of carbon of about 750 Pg C at the beginning of the simulations, circa 1850, the warming induced by anthropogenic CO2 emissions, following the "business-as-usual" scenario, leads to an average loss of carbon of 50 Gt C by 2100.

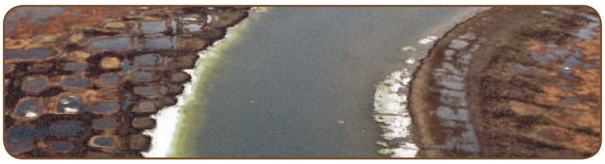
It has to be kept in mind, however, that there is a large statistical uncertainty on the actual warming associated with the increase in atmospheric CO2. That uncertainty will propagate into the calculation of the uncertainty in permafrost thawing and hence carbon loss.

By 2100 the amount of carbon remaining in the permafrost varies between 675 and 720 Gt C. However, as warming continues in the 22nd and 23rd centuries, permafrost carbon continues to decrease, with growing uncertainty. By 2300, the amount of carbon remaining in permafrost varies between 410 and 660 Gt C, with an average of around 550 Gt C. That is a loss of 200 Gt C, or about 25%of the initial stock.

There is very long inertia at play: the deep soil, similarly to the deep ocean, takes a very long time to reach a new equilibrium. It would take centuries after the CO2 emissions from permafrost had ceased for the carbon balance to eventually stabilize.

PAGE21-improved European global climate models show 50 Gt C average loss of soil carbon by 2100 following the "business-as-usual" (RCP8.5) scenario.

The PAGE21 results thus highlight that over the 21st century, the amount of carbon released from permafrost might not be as large as previously claimed. The project finds an average loss of about 50 Gt C, which is at the lower end of the previous IPCC AR5 estimates, those being between 50 to 250 Gt C. However, in a much warmer world the carbon loss would continue for centuries, leading to a severe degradation of permafrost ecosystems and large loss of previously frozen-in carbon.



What should we do next?

It is evident that the Arctic climate will continue to warm throughout the 21st century. Even if the global mitigation efforts do manage to cut greenhouse gas emissions down to zero by 2100, the Arctic will still be more than 2 °C warmer than in today's climate.

This warming is substantial, and will generate permafrost thaw that will have impact on the global climate through the permafrost-carbon-feedback. Current global climate policies, including the newly negotiated Paris Agreement at COP21, do not include permafrost-related greenhouse gas emissions. Likewise, global climate models are still lacking processes that play a significant role in determining the volume and speed of the permafrost-carbon-feedback.

Permafrost-carbon-feedback needs to be included into global climate discussions.

PAGE21 found that in addition to the physical processes that have now been included in the three European global climate models, there are additional processes related to the water bodies in permafrost regions that play a more significant role in the permafrost carbon balance than previously thought. To fully understand the permafrost-carbon-feedback, thermokarst, water-borne lateral fluxes and different hydrological processes in coastal and subsea permafrost areas will need to be investigated in more depth.

More than ever, there is also a need to understand the impacts of permafrost thaw not only at the global, but also at the regional and local level. Stakeholders must be involved in the efforts to develop new ways of addressing these changes through long-term monitoring and adaptation plans.

Impact assessments are needed involving local stakeholders.

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