Final Report Summary - PAGE21 (Changing Permafrost in the Arctic and its Global Effects in the 21st Century)

Executive Summary:
Our understanding of the physical and biogeochemical processes at play in permafrost areas has been greatly inadequate and significant gaps have existed in our knowledge, hindering any accurate assessment of the vulnerability of Arctic permafrost to climate change, or of the implications of future climate change for global greenhouse gas (GHG) emissions.

The PAGE21 project was designed to broaden our 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, the PAGE21 project has sought to answer the following questions:

· What are the key processes and parameters influencing and controlling the vulnerability of the carbon and nitrogen pools in Arctic permafrost to future climate change?
· How large an effect will Arctic climate change feedback (due to changes in the carbon and nitrogen pools contained in permafrost) have on anthropogenic global warming?

The results to date have highlighted that the amount of carbon released from permafrost over the 21st century may not be as large as previously claimed. The project has found an average loss of about 50 GtC by 2100, which is at the lower end of the IPCC estimate of 50 to 250 GtC. However, we have found that, in a much warmer world, this carbon loss would continue over hundreds of years leading to a severe degradation of permafrost ecosystems and a large cumulative loss of previously frozen carbon.

Project Context and Objectives:

Key questions:

According to one recent estimate (Tarnocai et al., 2009), the northern permafrost region contains approximately 1,700 Pg (1 Pg = 1 billion metric tons) of organic carbon, of which about 90% occurs in permafrost deposits. This represents approximately 50% of the estimated global below-ground organic carbon pool and double the amount that is contained in the current atmospheric carbon pool (Schuur et al., 2008). The sheer size of this carbon pool, together with the large amplitude of predicted arctic climate change (IPCC, 2007), implies that there is a high potential for global-scale feedbacks from arctic climate change if these carbon reservoirs are destabilized. A destabilization of 10% of these carbon pools and subsequent emission as CO2 would increase the atmospheric CO2 concentration by 0.1 ppm and, based on the Stern review (Stern et al., 2006), induce additional costs of 350 trillion Euros per year for the European Economy.

Despite these converging lines of evidence, significant gaps existed in our current state of knowledge that prevented us from producing accurate assessments of the vulnerability of the arctic permafrost to climate change, or of the implications of future climate change for global greenhouse gas (GHG) emissions. Specifically, our understanding of the physical and biogeochemical processes at play in permafrost areas was still insufficient...
in three key aspects; (1) It has been difficult to quantify the relative contributions of the previously frozen carbon (and nitrogen) pools to the mobilization of the anticipated gradual but widespread deepening of the active layer, and of abrupt disturbances such as thermokarst formation, thermokarst/river/coastal erosion and thaw slumps (Schuur et al., 2008). (2) Size estimates for the high latitude continental carbon and nitrogen stocks have been varying widely between regions and research groups, due to in part our still limited knowledge over a large area, to small-scale variabilities, and to the complexity of processes (e.g. cryoturbation), but also due to the use of non-standardized methods and upscaling. (3) The representation of permafrost-related processes in global climate models still tends to be rudimentary, and has been one reason for the frequently poor performances of climate models at high latitudes (IPCC, 2007).

These large knowledge gaps, the observed onset and projected acceleration of drastic climate and landscape changes in the Arctic, together with the threat of potentially large positive feedbacks of arctic permafrost to global climate change, have encouraged doomsday scenarios that have been popular in the media, and even in some serious scientific journals (e.g. Nisbet and Chappellaz, 2009). Clearly “more science, less hype” (Kerr, 2010) is needed to put these findings into perspective. This immediately leads to the following key questions that have been addressed by the PAGE21 project:

- What are the key processes and parameters influencing and controlling the vulnerability of the arctic permafrost carbon and nitrogen pools to future climate change?
- How large will the arctic climate change feedback be on anthropogenic global warming, via changes in the sizes of permafrost carbon and nitrogen pools?

The concept of the project is to directly address these questions through a close interaction between monitoring activities, process studies and modeling on the pertinent temporal and spatial scales.

Project Concept – process studies, monitoring and modeling:

PAGE21 contributes to enhance monitoring of permafrost in the Arctic by further developing measurement standards in permafrost science, by upgrading existing sites or developing new sites, and by embedding its site measurements and remote sensing generated layers in existing observing systems.

Each of the PAGE21 sites records a basic set of environmental and climatic parameters, providing a basis upon which the modeling component relies for parameterization and validation. In particular, borehole-based permafrost temperatures and active layer thicknesses have been made available for each site, as well as active layer moisture content, permafrost ice content and type, and meteorological measurements. Landscape-level inventories of soil carbon and nitrogen pools (quantity and quality) have been performed at each of the primary sites, assessing partitioning among land cover types and ground horizons (e.g. active layer vs. permafrost layer) and gas flux measurements performed at each of the PAGE21 primary sites.

The PAGE21 concept for the interaction between site-scale studies and large-scale modeling is to establish and maintain a direct link between these two disciplines for developing and evaluating, on all spatial scales, the land-surface modules of leading European global climate models (MPI-ECHAM6, HadGEM, and IPSL-CM5) taking part in the Coupled Model Intercomparison Project Phase 5 (CMIP5), designed to inform the IPCC process.

Expected Results:

The overarching aim of PAGE21 is to assess the vulnerability of arctic permafrost to climate change and to reduce the uncertainties in permafrost-related feedbacks to global change. It is principally against this objective that the success of PAGE21 is now measured.

To be able to better understand and predict future behavior of permafrost temperature and hydrological properties, there has
been a need for better information on the physical properties of the underlying substrate. (Romanovsky et al., 2010). Detailed information on ice content throughout the active layer profile, in particular, is required to better understand how changes in the ice and liquid water contents affect the ground thermal response.

Further, there has been a paucity of soil property data with regard to below-ground carbon pools in the Eurasian sector (Tarnocai et al. 2009). The number of pedons that include deeper cryoturbated organic-rich deposits (between 1-3m depth) from the continuous permafrost zone have been extremely limited. The new landscape-level inventories planned within PAGE21 were designed to significantly improve the Northern Circumpolar Soil Carbon Database. With these new detailed surveys, complemented by previous studies in Russia, Greenland and Alaska, the project aimed to perform, for the first time, a pan-Arctic statistical meta-analysis of the key processes and environmental variables governing the quantity and quality of permafrost carbon. Further, the project aimed at linking the soil property data to new land cover classification products that have a much higher resolution (1x1km and even 250x250m), allowing for a second, independent and potentially more accurate upscaling of the soil carbon dataset.

Climate change and permafrost degradation result in fluxes of water, sediment and dissolved elements across landscape types, which in turn influence the spatio-temporal variability of subsurface greenhouse gas production and consumption. This set of interacting biogeochemical and physical processes represents the key to an improved understanding of the delicate net balance of permafrost carbon and to predicting the release of carbon dioxide and methane into the atmosphere (Zimov et al., 2006; Schuur et al., 2009). PAGE21 integrated detailed large scale field manipulation experiments and detailed laboratory investigations of top permafrost cores and active layer samples into a process-based models that were used to assess both the potential for, and controls on, greenhouse gas production in thawing permafrost layers, as well as active layer consumption of methane and nitrogen. This included an assessment of both a near-freezing temperature-dependency of processes as well as long-term incubation experiments.

Ecosystem to atmosphere fluxes of carbon, nitrogen and greenhouse gases have been quantified at many sites since the 1980’s, using a variety of techniques (Van der Molen et al., 2007; Sachs et al., 2008). For the Arctic, there were however still many challenges to be met: the harsh and remote conditions have often restricted observations to the summer season, while recent data suggest that spring and autumn emissions may be particularly important with respect to the release of gases stored below ice and snow in winter, or gas stored in the soil that is driven out during freeze-up (Mastepanov et al., 2008). Spatial variability has also often been incompletely addressed; thermokarst lakes and ponds, as well as river floodplains, have recently been identified as important biogeochemical hotspots (Van Huissteden et al., 2005; Walter et al., 2006). Moreover, spatially integrating eddy covariance data for lower concentration greenhouse gases such as carbon dioxide and Nitrous oxide have been rare or absent due to power supply restrictions on the use of advanced gas concentration measurement equipment in remote locations. The project has improved the observational record of permafrost soils and ecosystems at a circum-Arctic network of sites. This is the first concerted effort to obtain a consistent data set for model validation, for quantification of processes and fluxes, and for measurement of temporal and spatial variability.

A range of previous investigations have also shown the potential for monitoring indicators of permafrost landforms over decadal time scales using satellite remote sensing at site-scale. Thermokarst lakes in particular, have been of great interest (e.g. Smith et al., 2005). There has been, however, still no clear distinction between interseasonal, intraseasonal and long-term changes in thermokarst lakes, at site-scale or at a circumpolar scale. In depth, across-scale and between-sites harmonized investigations into land surface changes (including vegetation cover) has thus been carried out within the PAGE21 project not only allowing comparisons between the chosen sites but also, for the first time, the creation of a circumpolar picture of land surface changes. Land cover, land surface temperature and surface wetness changes are remotely assessed at each site to provide quantitative understanding of spatial changes and heterogeneity for model validation.

The land-surface modules of most state-of-the-art coupled general circulation models have so far included only considerably simplified descriptions of the thermal and hydrological effects of soil freezing and related processes and properties (snow,
They have generally neglected the effects of sub-grid variability of landforms, soil types etc., which have a strong influence on the large-scale effects of these processes. Further requirements for correct simulations of the evolution of the high-latitude carbon and nitrogen pools include the ability of the model to simulate biogeographical changes in response to climate change and to represent the continental carbon cycle and, ideally, the nitrogen cycle, taking into account above- and below ground carbon reservoirs.

The three land-surface modules selected for PAGE21 (ORCHIDEE from IPSL-CM5; JULES from HadGEM; JSBach from MPI-ECHAM6) have been developed with these three features in mind. The initial developments have focused on thermokarst-related physical and biogeochemical processes and dynamics in JSBach; on improvements to the representation of physical processes within the soil, leading to a better representation of the active layer thickness and the relative saturation levels in soils in JULES; and on improvements to the representation of sub-grid soil moisture variability within the frozen and thawed soils as well as a better representation of snow physics and high-latitude vegetation particularities in ORCHIDEE.

The coordinated use of these specifically improved land-surface modules under climate change (prescribed and interactively simulated, i.e. in coupled runs with the host climate models) provides the most reliable evaluation of permafrost-related feedbacks to global climate change that has ever been produced, which represents a very substantial advancement beyond the current state-of-the-art. Moreover, based on the analysis of these simulated feedbacks, PAGE21 delivers the first assessment of the effect of the dynamics of permafrost pools on the probability that climatic stabilization can be attained using current scenarios.

Project Results:

Geocryological Mapping

One of the key objectives of the PAGE21 project was to evaluate the potential effects on periglacial landform activity from future and ongoing climatic changes in the various permafrost areas represented by the field sites of this project. To do so, and to upscale the local measurements of surface and subsurface parameters to landscape and regional scales, geomorphological and geocryological mapping was conducted in all primary PAGE21 field sites.

The primary PAGE21 field sites were selected so that they cover the existing environmental gradients from continuous cold permafrost to maritime warm sporadic permafrost environments in the Arctic, but also to cover the periglacial landscape variability occurring in Arctic permafrost areas from the very extensive sedimentary lowland landscapes of northern Eurasia to the mountainous highlands of northern Scandinavia, Svalbard and Greenland.

Geomorphic mapping is the characterization of landforms existing in an area. The mapping contains information on which types of sediments are found and which landforms exist in specific area. The size of the area to be mapped and the scale of the map will decide the level of details that can be included. The various PAGE21 key field sites have different physical sizes from the entire Lena Delta to a small catchment in the Ny Ålesund area in Svalbard. In addition, the project focused on mapping in larger details the lowlands and/or sedimentary parts of the landscapes, meaning that the mountain parts of the geomorphological maps might have less mapping resolution.

If a landscape contains a high amount of ice in the top permafrost layer, there might be significant changes in the landforms in case of climatic warming, increasing the active layer thickness and thus thawing the top permafrost or transient layer. To be able to predict such changes, geomorphological knowledge and understanding of the landscape in a form of geomorphological maps is necessary. In addition, we also need a quantification of how much ice is in the transient layer and top permafrost in order to be able to model correctly the response time for the expected changes to the landscapes.

Geocryology is the part of permafrost science and cryosphere studies that focuses on detailed understanding of the amounts and types of ice that exist in the permafrost. Cryostratigraphy differs from traditional stratigraphy by explicitly recognizing that perennially-frozen sediment and rock (permafrost) contain structures that are different from those found in unfrozen sediment and rock. Understanding the types of ice in the permafrost and the stratigraphy of the sediments enables reconstruction of genesis of the frozen sediments and thus the permafrost history of the different landforms.
As all the PAGE21 primary sites are either research station sites, or sites with very intensive research use, some basic mapping already existed before PAGE21 for most of these sites. Topographical maps and digital elevation models (DEMs) are natural background material on which to build the geomorphological and geocryological mapping. Also aerial photographs with high resolution have been used, just as satellite photographs have been included.

To quantify the amounts of ice in the top permafrost coring has been carried out in the PAGE21 key field areas in which no data existed prior to the project. Permafrost coring has been done primarily by using handheld motorized light weight equipment, which typically can obtain cores down to between 2-4 m below the terrain surface. If the coring was conducted during winter the active layer seasonal ice content was also determined, but generally the project focused on the ice content in the top permafrost. In some sites also deeper permafrost coring down to the level of the annual temperature variations, typically around 10 m depth, was carried out as part of the PAGE21 project. This was done using a medium size drill rigs. Permafrost cores were analysed in laboratories to determine gravimetric and volumetric ice content, when ever possible to obtain. As an example, 28 different landforms were identified in the Zackenberg study area, covering the range from glacial, periglacial, fluvial, lacustrine, and coastal landforms to exposed bedrock. On a more detailed scale, the landform-forming processes were identified and outlined by line features, such as solifluction lobes, flow lines on fans and debris flow tracks, or by symbols representing ice-wedge polygons, deflation surfaces, large erratics, etc.

Thermal state of permafrost and Active layer Dynamics

Analyses and comparisons of the permafrost physical dynamics were conducted focusing on the thermal state and active layer dynamics between all the primary PAGE21 field sites. Some of the sites had previous permafrost thermal observations established before starting the project, while others were established as part of the project. With unified research infrastructure the project was able to study and compare the permafrost physical dynamics across all the key Page21 field sites.

Generally, all sites collected permafrost temperatures from thermistor strings installed in cased boreholes, just as all sites have performed CALM (Circumpolar Active Layer Monitoring) network measurements. In the Russian sites it was unfortunately not possible to establish new deeper permafrost boreholes during the Page21 project due to a combination of permission and financial problems.

In NE Greenland at the Zackenberg site it became possible to drill the first permafrost boreholes deeper than 3 m in 2012 as part of the project, but only due to additional funding from several other sources such as from the Centre for Permafrost (CENPERM) at Copenhagen University.

In Svalbard several new 10 m deep boreholes were drilled using the medium sized drill rig that UNIS acquired, partially funded by the Page21 project, and temperature monitoring was established in some of these boreholes adding to the existing network of permafrost boreholes drilled earlier during the International Polar Year, IPY. Also shallow 2-3 m boreholes were drilled as part of the Page21 project in Svalbard and ground thermal observations started to cover the entire span of landforms and sediments in the Adventdalen valley area.

The recorded permafrost temperatures from the deepest level in common to all sites at 7 and 8 m in ice-wedge polygons at the overall scale reflect the difference in meteorology. At the two Russian sites the temperatures are the coldest, but not very much colder than at the NE Greenland, site, while Svalbard is somewhat warmer, Abisko being the warmest with below 0˚C temperatures. However, there are large differences between the sites with respect to annual variation, which is much larger (> 3˚C) in Russia than in both Zackenberg and Svalbard, which have annual variations in the order of 1˚C, whereas Abisko does not show a consistent seasonal pattern. Thickest active layer is found in Svalbard, and thinnest in Kytalyk in Siberia, but with the peat of the sporadic permafrost in Abisko at an intermediate level.

Generally the permafrost temperatures have increased during the period leading up to the PAGE21 recording period in Samoylov and Svalbard. In Samoylov the permafrost has warmed about 2˚C in the period from 2006-2007 to 2012-2013. However, from summer 2011 to summer 2013 no larger changes took place before a warming in summer 2014, which must therefore represent a winter warming. In Svalbard a warming of about 1˚C took place primarily from winter 2011 to late winter 2013, while the temperature has been more stable since then. In Kytalyk there is no distinct change. The only 2-year long time
series from Zackenberg shows a decrease of about 0.5°C. Also, Abisko recorded a very small decline in temperatures from 2008 to 2011, and since then no change.

Soil Organic Carbon

The strength of the so-called permafrost carbon – climate feedback first and foremost depends on the size of the total soil organic carbon (SOC) pool present in soils and deposits of the permafrost region. Another critical question is how quickly SOC will decompose following thaw. The size of the permafrost carbon pool and its decomposability will inform us about the potential future release of greenhouse gases from thawing permafrost, which represents a positive feedback on global warming (further increasing global temperatures).

The aim of the project was to improve our knowledge of the total storage, landscape distribution and soil horizon partitioning of soil organic carbon (SOC) in the northern permafrost region, as well as to assess its potential rate of decay following permafrost thaw. Overarching questions were how much SOC is stored in the soils and deposits of the northern permafrost region, which soils, landscape units and regions are SOC ‘hotspots’ (= quantity), how quickly will SOC decompose following permafrost thaw (= quality) and taking into account quantity and quality, which are the vulnerable permafrost SOC pools.

To answer these questions fieldwork was carried out across the northern permafrost region. Comprehensive landscape-level inventories of soil organic carbon storage were completed at all PAGE21 primary sites and some secondary sites. Samples were collected in soil profiles along transects that represent the variability of landscapes at the respective sites and transported back to Stockholm and Copenhagen where subsequent laboratory analyses took place to calculate SOC stocks and assess decomposability using simple geochemical indicators (Stockholm) and incubation experiments (Copenhagen).

Landscape level soil organic carbon (SOC) maps can now be produced for all our PAGE21 sites. They can be produced for a variety of soil depth intervals as well as for Nitrogen stocks, etc. These allow us to infer the regional and landscape level hotspots of SOC storage across the northern permafrost region. For instance, lowland areas (such as Lena Delta) store much more SOC than mountainous areas (such as Zackenberg). Large stocks are often associated with peat deposits, cryourbated soils, and eolian and river/deltaic deposits. Our data has contributed to the state-of-the-art Northern Circumpolar Soil Carbon Database, which had a paucity of data for the Eurasian and High Arctic sectors.

The potential decomposability of soil material from all sites was assessed either in a field laboratory or back at the University of Copenhagen. The Copenhagen samples were incubated at 5°C for up to 1 year, with measurements of C-CO2 production rates after 1, 7, 15, 40 and 48 months. The focus was on the relationship between simple geochemical indicators and decomposition rates to assess future carbon release from warming active layer and thawing permafrost soil layers.

These results show that:
- Decomposability decreases in the order top soil organic layer > active layer ≈ permafrost layer. Peat shows a particularly low rate of C-CO2 production. Much in-group variability remains
- The observed variability is greatly reduced when grouping samples according to landscape units, with decomposability decreasing in the order alluvial > eolian > mineral upland > peatland, with again lowest respiration rates in peat deposits

All results will be synthesized in a pragmatic classification of potential decomposability based on soil horizon partitioning and landscape unit characteristics useful for upscaling to the entire northern permafrost region. By combining quantity and quality indicators the vulnerable permafrost pools and regions can be defined:
- Peatlands are a major store of carbon in the northern permafrost region, but peat in our incubation studies seems quite slow to decompose suggesting lower vulnerability than can be expected based on SOC quantity criteria only
- On the other hand, soil material in alluvial (including deltaic) and eolian (including Yedoma) depositional environments displays high decomposability, which multiplied by the great depth of these deposits make them highly vulnerable carbon
Mineral upland soils, including those with buried carbon stocks due to cryoturbation and slope processes, display a relatively low decomposability.

A full synthesis of field and laboratory data collected at all primary and some secondary field sites of the PAGE21 project is currently in progress. With available data on SOC quantity and quality the project is able to update the Northern Circumpolar Soil Carbon Database with new SOC inventories, develop pragmatic classes for upscaling potential SOC decomposability to northern circumpolar scales, using simple soil horizon type and landscape unit criteria and identify vulnerable permafrost carbon pools, combining SOC quantity and quality criteria. This is a significant step in order to be able to assess the full permafrost carbon-climate feedback under global warming.

Greenhouse Gas Fluxes

PAGE21 was set up to provide for all PAGE21 observation sites throughout the Arctic, measurements that quantify the actual amount of greenhouse gases exchanged between permafrost ecosystems and the atmosphere. This quantity is also known as the greenhouse gas flux, in units of mass per area per unit of time. The second aim was to relate these fluxes to ecosystem characteristics such as vegetation type, the amount of soil organic matter and nitrogen compounds, climate, and permafrost characteristics. Third, the project aimed at better quantification of the uncertainty in arctic greenhouse gas flux observations, by comparison between measurement methods and equipment comparisons.

The research sites included northeast Greenland (Zackenberg, operated by Lund University), two sites in Svalbard (Adventdalen operated by Lund University, and Ny Ålesund operated by AWI), northern Sweden (Stordalen, operated by University of Copenhagen), northwest Russia (Seida, operated by University of Eastern Finland), two sites in northern Siberia (Samoylov Island in the Lena delta, operated by AWI and University of Hamburg and Tiksi at the coast of Laptev sea, operated by Finnish Meteorological Institute), northeastern Siberia, Indigirka lowlands (Chokurdagh/Kytalyk, operated by VU university Amsterdam, IBPC, Yakutsk and Hokkaido University, Japan), northeastern Siberia, Kolyma Lowlands (Chersky, operated by MPI) and central Siberia near Yakutsk (Spasskaya Pad, operated by IBPC). An associated site providing data is Daring Lake in Northern Canada. These sites cover a wide range of permafrost types, including sporadic permafrost to continuous permafrost, tundra, taiga, northern mire and lake environments.

Basically two methods of greenhouse gas flux measurement are being used in ecosystems. The first is eddy covariance: a technique which requires measurement of gas concentrations and wind speed in vertical and horizontal directions, at a very high sampling frequency: ten to twenty times per second. This method observes the flux of greenhouse gases from or to an ecosystem over a larger area upwind of the observation tower, depending on the height of the tower and air turbulence. Second, various types of chambers are being used, which are boxes that enclose the ecosystem to capture all greenhouse gas transfer to and from the atmosphere. Measurements of gas concentration changes inside the chamber allow calculation of the flux; it requires frequent gas sampling or field-based gas analyzers. Measurement of carbon dioxide fluxes is relatively easy, but low concentration trace gases like methane and nitrous oxide require more sophisticated analyzers.

These techniques provide for carbon dioxide the Net Ecosystem Exchange (NEE), which is the net flux between the ecosystem and the atmosphere; for carbon dioxide this is the sum of uptake by photosynthesis (negative sign) and losses by respiration including soils (positive sign). Methane fluxes are predominantly released from ecosystems into the atmosphere (positive sign), but can also have a negative sign in drier soils when methane consumption by bacteria exceeds its production. For a comprehensive overview on an ecosystem carbon budget, also water-borne (lateral) carbon fluxes (organic matter transported by streams) need to be considered; these can be obtained from water discharge measurements and water sampling, and were included for parts of the PAGE21 observation network.

The projects ambition was to establish field sites that facilitate year-round flux measurements, based on rugged...
instrumentation that allows inclusion of the harsh Arctic winter season. With this ambition, the PAGE21 research groups worked at the limits of current greenhouse gas flux measurement techniques. All instruments require continuous power supply that is usually not available in remote Arctic sites, meaning that at several sites autonomous power supply by solar panels, wind generators or diesel generators needed to be established. Moreover, the instrumentation had to withstand winter temperatures going well below -40°C. Logistics for transport of equipment and fuel supply for the sites are also challenging. Starting a new site in Siberia requires thorough preparation, including obtaining permits for use of instruments. The Chersky site could not start observations until after the first year for these reasons; other sites could continue with observations that were already started from previous research projects.

Obtaining full-year flux measurements is important, because of considerable uncertainties with respect to greenhouse gas exchange patterns in late autumn, winter and early spring. Carbon cycle processes in these colder seasons may result in high flux peaks, as demonstrated at the Zackenberg site. This goal has not been met for all sites, because of inevitable equipment and power supply failures and difficult logistics in winter conditions. Nevertheless, at all sites the project managed to extend flux measurements well into autumn and spring. This extended data coverage has demonstrated the occurrence of high emissions related to winter soil freezing and melting of snow and lake ice in spring. It also demonstrates the importance of continuous monitoring of greenhouse gas fluxes from permafrost environments, leading to the conclusion that future improvements in understanding year-round Arctic flux patterns needs support with a sufficient budget.

The second aim, i.e. relating fluxes to ecosystem, soil, climate and permafrost characteristics, was based on close cooperation with other research fields within the project. Work package 2 mapped permafrost ice content and other permafrost characteristics at each site; work package 3 provided data and maps on soil carbon stocks and their lability, and soil nitrogen. Work package 5 provided remote sensing material for upscaling of fluxes. The first workshop on inter-site comparison was organized during the General Assembly in Abisko in 2013. During that workshop, also a pathway was determined to arrive at a uniform processing of all eddy covariance raw data in order to make an intercomparison between the sites more meaningful by e.g. excluding artifacts created by different approaches in data processing.

The third aim, i.e. improved quantification of uncertainties in arctic greenhouse gas flux observations, was also approached by this uniform data processing. However, during the first work package meeting in Copenhagen in 2012, it also became clear that a full harmonization of instrumentation and data processing for each site was not feasible, because it would require replacement of existing instrumentation in most cases. A major enterprise was the collection of all flux data in the European Fluxes Database. Within this database, hosting flux data from many European flux measurement sites, a separate section for PAGE21 data was established.

In the course of the observation years, considerable progress was made at each site on process understanding of fluxes. At Zackenberg, Lund University focused on the processes behind methane emission bursts that occur during soil freezing, and pioneered in using isotopic analysis of methane to unravel methane sources. At Stordalen, fluxes of methane from subarctic mire and a lake were studied, showing in particular spring methane bursts. Seida concentrated on processes behind nitrous oxide emission from bare peat patches, and analysis of methane sources. At Samoylov and Kytalyk, research was done on the effects of thaw ponds on local greenhouse gas emissions, and on improving the partitioning of measured net CO2 fluxes between gross primary production (photosynthesis) and ecosystem respiration (carbon release by decomposition and plant respiration). At Chersky, a unique drainage experiment was monitored with two eddy covariance towers, showing the effects of changes in soil water levels on methane production and NEE of carbon dioxide. Most sites also conducted separate analyses to monitor the fluxes for various vegetation and soil units at the sites, by performing 'footprint' analysis to determine the source of the eddy covariance fluxes, and to compare with fluxes collected with chamber methods.

At the General Assembly in 2014 in the Netherlands, several potential integrative research papers were proposed, combining results from all work packages. This was further consolidated during the interim General Assembly in 2015 in Exeter. Planned integrative papers include inter-site flux comparison, upscaling of carbon dioxide and methane flux data, and exploring the
relation between fluxes and permafrost soil carbon pools. In addition, all research groups will produce papers on site-specific results.

In 2015 also data submission to the database of all sites was nearly completed. Several sites have observation records of more than 10 years of data, including those collected during the PAGE21 years. At the General Assembly in Iceland in 2015, a meta-analysis of 59 site-years of data could be presented, which is a solid base for the first integrative paper. The carbon balance for all sites could be analyzed and compared, showing that at most sites about 64% of gross primary production is respired again.

This meta-analysis also shows clear relations of yearly carbon dioxide fluxes and soil carbon pools, growing season length, thaw season length, air temperature sum, precipitation and incoming solar shortwave radiation. In particular the impact of growing season length, air temperature, precipitation and carbon pools on carbon cycle processes are important to understand the effects of future climate change.

The data collection within the PAGE21 framework finished in 2015. For most sites, PAGE21 has contributed to the expansion of the observation record to longer time series of flux data; at Chersky a new site could be established. This long term monitoring is crucial if we want to understand the effects of climate warming on permafrost ecosystems, and understand the feedbacks between permafrost thaw on global warming.

Remote sensing

The remote sensing component of the project produced advanced datasets related to permafrost processes, carbon pools and fluxes. Scaling and validation issues were also addressed. Special emphasis was on the utilization of some active and passive microwave data, which are cloud cover independent. Thermal as well as surface water related datasets were produced and validated. Time series of land surface temperature and surface soil moisture records have been extracted from existing databases for all high latitude boreholes and submitted to the GTN-P database as meta information.

Special attention was given to the production of comparable datasets for all sites. This includes the utilization of dedicated monitoring schemes (covering standardized pan-Arctic land cover information, site-scale terrain changes, and multi-scale and multi-sensor land surface temperature monitoring from recent years). Especially JAXAs ALOS archives have been shown suitable to produce remotely sensed site maps. Significant inter-annual and intra-annual variations of open water extend have been identified for several PAGE21 sites using ENVISAT ASAR records. TerraSAR-X could be shown applicable for quantification of coastal erosion rates in the Lena Delta.

Further on, in situ data from the PAGE21 sites were used for the validation of coarse to medium resolution datasets (land surface temperature, surface soil moisture and landcover classes) with respect to use in modelling and upscaling. Issues related to landscape heterogeneity, which are specific for the Arctic, have been addressed for surface temperatures (CEA-LSCE, supported by University of Sherbrooke) and land surface hydrology (TUW). Medium spatial resolution remotely sensed data have been utilized to evaluate and support the application of global coarse resolution datasets (>20km) in arctic and subarctic environments. All datasets are delivered via registration in PANGAEA database.

SSM/I brightness temperatures at 25 km resolution and at both vertical and horizontal polarizations were used to inverse land surface temperatures (LSTs). A novel methodology was developed to recalibrate the SSM/I various sensors using MODIS-LST products. The combined use of ERA-LST Analysis allows to interpolate the LST instantaneous estimations and to produce hourly time series during snow free periods (André et al., 2015). These LSTs have been evaluated at local and global scale with MODIS-LST data at 1 km resolution over a seven-year period (2004-2010) and during the snow free period. The validation results at local scale over the 5 PAGE21 sites considered in a first step (i.e. Abisko, Samoylov, Daring Lake, North Slope and Cherskii) show that the LST product presents a RMSE of 1.7 K and a small bias of -0.1K with MODIS data. At circumpolar scale, the bias is 0.3 K and the RMSE is 2.2 K with MODIS data, which appears quite satisfactory, compared to previous works.
Finally, the time series have been gap-filled with ERA-LST analysis during the snow period to produce annual hourly and daily average LST continuous time series covering the whole year, in which the origin of the data are precisely flagged. These LST time series at hourly time step and daily averages were produced at 25km resolution over the 11-year period (2000-2010) and over the circumpolar Arctic (latitudes above 45°N). They represent an important and unequalled dataset for climate model evaluation and large scale analysis of surface energy budget processes. The daily data are available on the PANGAEA website (http://doi.pangaea.de/10.1594/PANGAEA.833409) and the hourly data are available from CEA-LSCE team.

Secondly, the LST data have been downscaled on the 12 PAGE21 sites. LST downscaling is based on high-resolution land cover mapping and data assimilation of the coarse resolution SSM/I LSTs in the ORCHIDEE land surface model. It is assumed that land cover is the major factor for surface temperature spatial variability inside the 25km scale SSM/I pixel. The SSM/I LSTs dataset was therefore assimilated in the ORCHIDEE model implemented on a 25 km grid, via a particle filtering technic, to estimate the LST of each land cover class present inside the pixel, assuming therefore that LST is the same for a given land cover class and a given SSM/I pixel at a given time. The retrieved LSTs were finally used to produce LST maps at 300m resolution, using the CCI-Land Cover product. The 300-meter downscaled temperatures have been further validated using MODIS-LST data at 1 km resolution. The comparison at 1km scale shows a quite good agreement with biases ranging from 0 K to 1.4 K and RMSE ranging between 2 and 3 K, depending on the sites. A more thorough evaluation was then performed accounting for vegetation cover and spatial heterogeneity for each site. It allows showing that RMSE are strongly dependent on pixel heterogeneity and land cover class errors. When considering pixels presenting a majority class, biases and RMSE were improved, showing the benefit of the downscaling to reproduce the inside pixel spatial variability. The maps are provided at hourly and daily time step and at 300m resolution around all the PAGE21 sites. They can be used to assess evaporation fluxes and help to perform upscaling. The daily values can be downloaded on PANGAEA website (http://doi.pangaea.de/) and hourly values are available from CEA-LSCE team.

The applicability of global surface soil moisture datasets has been addressed utilizing the concept of temporal stability, taking into account masking of frozen ground conditions. ENVISAT ASAR data (1 km resolution) have been analyzed in order to determine the applicability of coarser resolution datasets (esp. Metop scatterometer derived soil moisture with 25km resolution). A combination with Sentinel 1, as proposed, has not been possible due to delayed launch of the satellite. Uncertainties related to land surface heterogeneity (lakes) have been further addressed by investigation of ENVISAT ASAR WS (75m nominal resolution, but limited spatial and temporal coverage) as well as land surface model comparison (ORCHIDEE). The impact of wind action on tundra lakes for soil moisture retrieval has been quantified (e.g. up to 15% additional saturation in case of the Lena Delta) and an approach for correction developed. This novel method can be used in any environment with a significant proportion of open water. In-situ measurements have been collected from project partners and new stations deployed in order to further evaluate the products and to assess the representativeness of the sites for upscaling purposes. So far only near surface records were available for Alaska. The new measurements have been made in the Lena Delta and thus extent the records to Siberia. They provide insight into near surface moisture variations and influencing environmental conditions.

ENVISAT ASAR data (1 km resolution) were further investigated for the development of a novel circumpolar wetlands map with respect to upscaling needs regarding carbon pools and fluxes. Spatial and temporal inundation dynamics have been made available for Siberia based on ENVISAT ASAR WS (75m nominal resolution, limited spatial and temporal coverage). The extension to a circumpolar product is impeded due to to-date unavailability of Sentinal-1 data. Global wetland maps have been assessed with SAR data in addition for high latitude permafrost regions. These coarse resolution records have been shown problematic in mountain regions and in the proximity to coasts (where most PAGE21 are located), but can be used to identify wetting and drying trends.

A method for upscaling of carbon pools at site scale was introduced by WP3 (Soil organic carbon part of the project) in the course of the project. The potential of this method for circumpolar application has been investigated within remote sensing
component. Parameters relevant for geomorphological observations and carbon pools have been mostly selected from existing databases. Results suggested that an alternative approach as detailed by WP3 is required for circumpolar assessment. A new method was therefore proposed which provides more detail for SOC (Soil Organic Carbon) patterns in the Arctic than the existing NCSCD (Northern Circumpolar Soil Carbon) v2.2 dataset. SOC within the top 100 cm can be estimated in tundra regions.

Further on landscape units have been derived. The landscape units reveal similarities between North Slope Alaska and the region from the Yamal Peninsula to the Yenisei estuary. Northern Canada is characterized by the same landscape units like western Siberia. North-eastern Canada shows similarities to the Laptev coast region. PAGE21 sites represent 9 of the 12 units (taking into account location in transition zones between units). The three remaining units are characterized by high slope gradients.

The novel map for upscaling fluxes has been developed which can serve as substitute for conventional land cover maps. Land cover is of prime interest for upscaling of carbon pools as well as fluxes. A challenge in the Arctic is the representation of land cover, specifically wetlands and water bodies. Due to unsatisfactory available land cover descriptions (including the 2014 released ESA CCI land cover map) a novel approach to describe arctic landscape has been developed. A circumpolar wetland map has been produced at 1km spatial resolution, which represents the dry, medium and wet conditions as well as sandy surfaces. Both new methods (production of SOC and the wetland map) have been tested for application on site scale (75m) and assessed with datasets available through WP3. 25% of the land area north of the tree line has been identified as wetland while conventional maps state 1-7%.

Of high relevance for permafrost biogeochemical processes is frozen status. Surface frozen status (frozen/unfrozen) related products have been derived from the ESA DUE Permafrost service. This includes the length of unfrozen period, first unfrozen day and first frozen day. Flux measurements from WP4 confirm the relationship between unfrozen conditions and carbon uptake. Satellite derived surface LST and status products can be therefore used to determine the length of the carbon uptake period, especially the end.

In addition, vegetation greenup dates have been estimated from SPOT-VGT data on a 15-year period (between 1998 and 2012) for various regions in the Arctic including 7 sites of PAGE21, observable by the instrument (latitudes less than 72°N). The datasets were produced by CEA-LSCE with the support of PRODIG team (University Paris-Diderot) These sites are: Kytalyk, Cherskii, Vorkuta, Nadym, Abisko, Herschel Island and Daring Lake and the datasets are available on PANGAEA at 1km scale and each year (http://doi.pangaea.de/10.1594). The algorithm uses a validated methodology proposed by Delbart et al., 2005, based on the analysis of time series of visible spectral indices specifically chosen to separate vegetation and snow variability effects. These dates are valuable data to validate ecosystem models simulations able to simulate vegetation seasonal dynamics. They provide complementary information for carbon fluxes modelling and upscaling. The data are available on PANGAEA and upon request from CEA-LSCE and PRODIG.

Global Climate modeling

Climate models are the only scientific tools that can be used to predict the evolution of the climate in response to human greenhouse gas emissions. They are large systems of physical equations, translated into computer language, that are solved by supercomputers in order to simulate the way the atmosphere, the ocean, the land surface and the ice evolve, with a time step of a few minutes and at a horizontal resolution of a few hundred kilometres. That means that the supercomputer calculates the evolution of the climate system, on an hour-by-hour, day-by-day, season-by-season, year-by-year basis, over decades and centuries.

A large number of complex climate-relevant processes are taken into account: Atmospheric and ocean circulation, cloud formation, radiative transfer, convection, rainfall, snowfall, evaporation of water from the soil and the ocean, snowmelt, and many others. In short, climate models simulate the weather like weather forecast models do, but they do it on longer time
scales, and the scientists using them are not interested in a prediction of the weather on some day in a distant future, but in predicting the average future weather, that is, the future climate.

In the latest IPCC assessment report a business-as-usual scenario (called RCP8.5) where emissions continue to grow over the 21st century, nearly tripling by 2100 relative to current level, climate models simulated a global warming of about 3.7°C by the end of the century, relative to present-day. Warming is predicted to be much larger in high latitudes, because of feedbacks in the climate system, such as reduction of spatial coverage of snow and sea-ice. Snow and ice are very efficient reflecting the solar radiation; this is what we call a high albedo. Oppositely ocean surface, vegetation and soil have a much lower albedo, absorbing much more solar energy. Hence, the high latitude warming leads to ice melt, reducing albedo locally, leading to more energy absorbed by the surface, reinforcing the warming in these regions, this is a positive feedback. For the same business-as-usual scenario, climate models predict a warming of about 8.3°C by the end of the 21st century for the Arctic regions (67.5°N to 90°N), that is more than double of the global average warming. For the very aggressive mitigation scenario (called RCP2.6) where global emissions of greenhouse gases start declining in the coming decade, are halved by 2050, and near zero by the end of the century, global warming is about 1°C relative to present-day, but warming of Arctic regions is again much larger, about 2.2°C.

The large warming of the high latitudes can have a major impact on Arctic ecosystems, in particular for permafrost. There is a large amount of carbon currently stored in permafrost. This carbon has slowly accumulated over thousands of years, thanks to the very cold conditions that prevent microbial activity and decomposition of soil organic matter. Hence, this “frozen” carbon has been locked away from the atmosphere for very long time. The ongoing warming and thawing of permafrost would make this carbon reservoir available for microbial decomposition, leading to carbon dioxide (CO2) or methane (CH4) emissions to the atmosphere. Emissions of these two greenhouse gases from thawed permafrost would lead to additional warming, generating a positive feedback. The latest climate assessment from the IPCC (Intergovernmental panel on Climate Change) concluded that: “It is virtually certain that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. By the end of the 21st century, the area of permafrost near the surface (upper 3.5 m) is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) for the model average (medium confidence). The release of CO2 or CH4 to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for RCP8.5 (low confidence). In short the IPCC is quite confident that permafrost area will continue to decrease over the 21st century, with larger reduction for larger climate change (RCP8.5) but it has low confidence on the amount of carbon being actually released to the atmosphere. For the RCP8.5 scenario, the best estimates vary by a factor of 5, from 50 GtC to 250 GtC.

Model improvement and evaluation

Until recently, in spite of the many important processes taken into account in climate models, many permafrost-related processes were not taken into account. The overarching goal of PAGE21 was therefore to improve the way climate models take into account and represent permafrost processes. This was required to pave the way for better projections of the future evolution of the climate system that take into account the influence of permafrost changes in the climate system, another modeling related task within PAGE21.

Scientists in PAGE21 worked on land-surface modules of three major European global coupled climate models used in the CMIP5 intercomparison project designed to inform the IPCC 5th Assessment Report, these being JULES (included in the HadGEM coupled climate model), JSBach (part of ECHAM6), and ORCHIDEE (coupled to IPSL-CM5). The essential processes that needed to be included in these climate models were:
- Soil freezing. Surprisingly, many climate models still do not account for the freezing of soil water at temperatures below 0°C, and its effects on soil thermal evolution and on hydrology. For example, melt water infiltration into frozen soils is impeded by the fact that ice lenses quickly form in the frozen soil, preventing soil water to tickle down.
- Stopped soil carbon decomposition below freezing temperatures. At low temperatures, soil microbes become inactive and stop degrading organic material. This is one of the reasons for large soil carbon accumulation in permafrost areas.
- Specific boreal vegetation types. Many climate models only very crudely represent vegetation types that are typical for tundra areas with permafrost. In many cases, tundra vegetation is assimilated to simple grasses. In particular, mosses are a very specific high-latitude plant type that thermally isolates the underlying soil, preventing summer heat from penetrating into the soil, and thus protecting permafrost.
- A detailed, physical representation of snow physics. Many climate models simulate snow in a very simple manner, leading to problems in the underlying soil.
- Cryoturbation. Regular freezing and thawing close to the surface induces slight movements in the soil that lead, over decades, to transport of organic material into deeper soil layers below the permafrost table. This is often not represented in climate models.
- Thermokarst. When ice-rich permafrost thaws, local depressions form, and water can accumulate in these. The effect and evolution of these small lakes is not represented in climate models.

The objectives of the project were thus:
- To add the missing permafrost-related processes in climate models used for IPCC assessments of future climate change;
- To evaluate these climate models by comparing their output to measurements of carbon and energy fluxes at selected PAGE21 permafrost sites;
- To produce assessments of present-day carbon reservoirs and fluxes on circumpolar scales.

Over the four years of PAGE21, and in particular during the first years of the project, much effort was made to improve the climate models by introducing several of the missing permafrost-related processes mentioned above. Progressive improvement of the climate models over the course of the project yielded a much better representation of physical, but also biogeochemical variables. The most important variable with respect to the general aim of the PAGE21 project is undoubtedly the permafrost carbon reservoir. The fact that it had not being taken into account in IPCC-class climate models so far was one, if not the most prominent, motivation for this project as a whole.

The developments applied to the PAGE21 models over the course of the project did indeed lead to a substantially improved simulation of the present-day soil carbon reservoir in permafrost areas, compared to observations. In addition, it is remarkable that not only strictly permafrost-related aspects of the climate system have been improved over the course of the project, but also, for example, the simulated river discharge of the main arctic river catchments. The improved simulation of such variables has important effects on the coupled climate system, because it can strongly influence the Arctic Ocean circulation. Moreover, the improved representation of permafrost-related processes not only changes the way present climate and permafrost is simulated in the present climate, but it also affects the simulated future evolution of permafrost, that is, how sensitively permafrost reacts to future climate change. An improved snow scheme can lead to substantial changes in the way an atmospheric change signal is transmitted into the soil below the snow surface. In particular, the modified snow scheme reduces the temperature change below the soil surface during spring, due to a more realistic thermal insulation capacity of the snow cover and differences in the changes of snow seasonality between the two model versions. This, in turn, will have effects on the simulated evolution of the permafrost carbon reservoir, which is very sensitive to temperature.

Carbon flux and reservoir assessment

During the initial phases of the project, the PAGE21 modeling groups participated in an international assessment of the evolution of pan-Arctic soil carbon fluxes and reservoirs. The models were run for the 1960-2009 period. It became quickly apparent that almost all of the models simulate an increase of soil carbon storage during that period. This means that during that period, there is no sign of the onset of a potential positive permafrost carbon feedback to climate change. Instead of
losing permafrost carbon to the atmosphere because of soil warming, the models simulate an increase in soil carbon due to increased vegetation productivity over the second half of the 20th century.

Updated Climate Simulations

The PAGE21 used the newly developed Earth System Models (ESMs) described above to revisit the vulnerability of permafrost carbon over the 21st century and beyond. Improved models, when evaluated against relevant observations can be used to investigate the response of permafrost soils and their carbon storage to future climate change. Technically this could be done in what we call an “offline” mode, where the permafrost model is driven by prescribed future climate fields (future surface temperature, precipitation, radiation,...); these fields having been simulated by standard climate models (that do not include permafrost). This approach is not fully consistent but it has the advantage of being computationally much faster, as land surface model with permafrost is several order of magnitude faster than a full climate model that also needs to simulate the atmospheric and oceanic circulation, energy and water budgets, etc. The alternative approach, called “online” mode, is to actually perform the future simulations with the coupled Earth System Models with the new permafrost component fully integrated in the model. The main advantage of the online simulations is that they allow estimating the feedback of permafrost carbon loss on the climate system. We performed both types of simulations within PAGE21, first in offline mode, then in online mode.

Using future climate forcing for the entire 21st century, the PAGE21 models simulate the evolution of permafrost extension. Continued warming always leads to reduction of permafrost extend. The active layer depth (ALT), defined as the depth at which the soil thaws in summer and freezes in winter, always increases at high latitude, indicating that soil are getting warmer, not only at the surface, but also at depth. Depending on the model used, the extension of permafrost reduces by 16 to 37 % for the RCP4.5 scenario and by 30 to 75% for the RCP8.5. Despite being significant, these reductions are notably lower than the one from IPCC (models average of 81% for RCP8.5). The main reason for our lower estimates here is the inclusion of key processes, such as moss and snow insulation, inclusion of organic soil, and better representation of the deep soil dynamic. All these processes tend to attenuate the propagation of warming from the surface to greater depth, hence reducing the progress of soil thawing. Nevertheless, we simulate a shrinking of permafrost areas at a rate of about 0.5 millions km² per decade. This rate implies that the entire permafrost would be thawed over several centuries if warming continues.

As a result of thawing, permafrost soils start releasing carbon to the atmosphere through enhanced soil organic matter decomposition by microbial activity. Starting from an initial stock of carbon of about 750 GtC at the beginning of the simulations, circa 1850, the warming induced by anthropogenic CO2 emissions, again, following the RCP8.5 scenario, leads to an average loss of carbon of 50GtC only by 2100. In those simulations, we investigated the uncertainty coming from the climate sensitivity of the climate system. There is indeed a large uncertainty on the actual warming associated to the increase in atmospheric CO2. That uncertainty will propagate into an uncertainty in permafrost thawing and hence carbon loss. By 2100 the amount of carbon remaining in permafrost varies between 675 and 720 GtC. However, as warming continues in the 22st and 23nd centuries, permafrost carbon continues to decrease, with growing uncertainty. By 2300, the amount of carbon remaining in permafrost varies between 410 and 660 GtC, with an average around 550GtC. That is a loss of 200 GtC (about 25%) relative to the initial stock. It is clear that permafrost degradation would continue beyond 2300. There is a very long inertia at play, the deep soil, similarly to the deep ocean, takes very long to reach a new equilibrium. It would take centuries after CO2 emissions cease for permafrost and its stored carbon to eventually stabilize.

The PAGE21 results highlight that over the 21st century; the amount of carbon released from permafrost might not be as large as previously claimed. We find an average loss of about 50GtC, at the lower end of the IPCC estimate (50 to 250 GtC). However, we find that carbon loss would continue for centuries in a much warmer world, leading to a severe degradation of permafrost ecosystem and large loss of previously frozen carbon.
Data Management

The high amount of data output from PAGE21 illustrates the importance of sophisticated data management in large EU projects. In the first phase of the project, the data management group conducted data requirement workshops to identify the special needs of the involved scientists to facilitate data exchange between the work packages. To be able to provide permafrost data in standardized format, data mining was conducted focusing on permafrost temperature (Thermal State of Permafrost – TSP) and active layer thickness (ALT) data. Additionally other variables were involved on request of the involved scientists.

The main product of the project data management component is the Data Management System (DMS), which is designed to be sustained also beyond the PAGE21 project. The DMS was closely linked to the Global Terrestrial Network for Permafrost (GTN-P, gtnp.org) a network established in 1999 by the International Permafrost Association under the Umbrella of the Global Climate Observing System (GCOS) and the World Meteorological Organization (WMO). The DMS is designed to facilitate the GCOS established “Essential Climate Variable” (ECV) “Permafrost”, which has further been defined by GTN-P as ground temperature and active layer thickness. The identified data during PAGE21 data mining for these two ECV’s have been assigned to PAGE21 sites together with soil moisture, snow depth, air temperature as well as surface temperature and moisture values from MODIS satellite data (ESA DUE Permafrost). All data have been standardized and implemented into the PAGE21/GTN-P Database (gtnpdbdatabase.org).

To collect, archive and disseminate the PAGE21 data, a data output catalogue was developed and implemented as online database available on the project website www.page21.eu. According to the needs of data quality control, the data have been stored in the PANGAEA Database, the European Fluxes Database and the GTN-P Database. Metadata information relevant to the PAGE21 community has been listed in the PAGE21 data output catalogue and linked to project reports and further data descriptions provided by the PAGE21 work packages. The total number of PAGE21 data sets listed in the output catalogue is 101.

The PAGE21 worked closely together with the Permafrost Young Researchers Network (PYRN) on several conferences and conducted workshops on data management to train and involve the next generation of permafrost scientists in best practices for data management, particularly related to the PAGE21/GTN-P DMS.

Further, the spatial structure of the available monitoring sites in all permafrost regions of the Arctic, Antarctic and Mountain areas was statistically analysed and the results have been published in an scientific article in the journal Earth System Science Data (ESSD). The next paper from the data management group was associated to the GEOQuebec2015 conference (Canada), outlining the combined PAGE21 and GTN-P strategies for permafrost data quality and assurance. In collaboration to the GEOQuebec conference, PAGE21 data management component conducted a workshop on data policy and data quality during which the concept for a report on the thermal state of permafrost was developed and planned for 2016.

Potential Impact:

Impacts

PAGE21 is an integrated multidisciplinary project, with the main objective of reducing the uncertainties associated with the processes and dynamics that affect the size of the arctic carbon and nitrogen pools, improving scientific monitoring programs in permafrost zones and feeding the results into global monitoring programs, enhancing modeling through the direct integration of field-gained knowledge, and improving future climate projections and the subsequent stabilisation scenarios. In this way, PAGE21 contributes to an enhanced understanding of interactions between climate and permafrost ecosystems.

By strengthening the monitoring efforts already existing in the Arctic, the PAGE21 project significantly improved the monitoring of permafrost related processes in the area. The project lifted measurement standards in permafrost science,
upgrading existing sites or developing new sites and embedding its site measurements and remote sensing generated layers in existing monitoring systems. PAGE21 chose its observing sites to maximize interactions and overlap with EU-supported initiatives, such as the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT), the Circumarctic Network of Terrestrial Field Bases (SCANNET), and the ESFRI’s SIOS project. This carefully prepared cooperation with existing networks operating in the Arctic ensures rapid and robust use of PAGE21-produced datasets within broader scientific communities.

For permafrost, PAGE21 both used and provided measurements to the Global Terrestrial Network on Permafrost (GTN-P), the monitoring network managed by the International Permafrost Association (IPA) on behalf of the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS). The permafrost temperature and active layer data were directly fed in the data management system of the GTN-P, which has been designed and programmed within this project. The database contains now time series for borehole temperatures and grids of active layer thickness plus air and surface temperature and moisture (DUE Permafrost, MODIS) measured in the terrestrial Panarctic, Antarctic and Mountainous realms. Metadata and data of both Thermal State of Permafrost (TSP) and Active Layer Thickness (ALT) have been further processed to complete the statistics on spatial structure, trends, and variability in comparison to the spatial distribution of climate relevant environmental parameters. Within the data management system the automated calculation of the depth of zero annual amplitude was developed which can serve as an additional variable for global models and be implemented in the NetCDF files. The PAGE21/GTN-P database (ISSN 2410-2385) is hosted at the Arctic Portal in Akureyri, Iceland and managed in close cooperation with the Alfred Wegener Institute for Polar and Marine Research in Potsdam, Germany.

Uncertainties in estimates of below-ground organic carbon and nitrogen in the northern circumpolar region, as well as in their re-mobilization and associated feedbacks to global climate change, have been large and resulted from a broad range of historical, logistical and scientific factors. These uncertainties relate to the relatively little soil property data availability for certain geographic sectors and for the deeper cryoturbated horizons, as well as to the uneven distribution of carbon and nitrogen within the landscape, the large polygon size used for upscaling in soil maps, the inadequate knowledge of carbon quality and lability, the lack of studies on the impact of permafrost processes on the release of these soil organic matter pools, and to the generally crude representations of arctic climate processes in current climate models. The PAGE21 project addressed and quantified a number of these uncertainties associated with the dynamics of the carbon and nitrogen cycles in permafrost. In particular, the project resulted in a better understanding of the three dimensional distribution of soil carbon and nitrogen, as well as the quantitative nature of permafrost processes affecting the size of the carbon and nitrogen pools, the uncertainties caused by the upscaling of field measurements, the seasonal cycle of gas fluxes, the quality and lability of soil organic matter, and hence ultimately also provided a better understanding of the feedbacks of the arctic permafrost carbon and nitrogen pools to global climate change.

The improvement of future climate projections is closely linked to the uncertainties described above. The PAGE21 project drew on the integrated observations and state-of-the-art models to improve both quantitative and qualitative predictions of the feedback of arctic carbon pools to the global climate. The project’s outputs provide a major contribution to the EU’s ambitious commitments to combat climate change through integrated mitigation policies.

As a result of the work on the physical parameterizations of permafrost-related processes, PAGE21 was able to quantify the future carbon balance of the arctic soils and vegetation. The improved quantification of the future carbon balance of arctic continental regions was followed by an evaluation of current stabilisation scenarios, and the establishment of updated climate model scenarios. Through the close contacts with political stakeholders and the participation of several leading members of the IPCC Working Group 1 in PAGE21, the project is likely to have a direct impact on the 6th IPCC assessment to be produced over the next 5 years, and hence on the UNFCCC’s climate policies and the ensuing protocols.
The dissemination process was designed to spread information among all potentially interested stakeholders, all levels of policy-makers (European and national), universities, and European citizens in general. In that work, the project relied on an outreach position at the Arctic Portal in Iceland ensuring that a consistent flow of information was provided at regular and frequent intervals, throughout the duration of the project. The Arctic Portal has extensive experience in bridging the gap between the scientific community and wider audiences such as policy-makers and the general public. It was responsible for publicizing the scientific field activities and displaying project information and results on widely accessible networks such as YouTube, Facebook or Twitter and to contribute to educational and e-learning material on permafrost, to be supplied to the project website and displayed on the International Permafrost Association website.

The project website was one of the main tools for outreach and data dissemination. It consists of two parts - a password protected area with capabilities for document sharing, progress monitoring and reporting, and a public website allowing external access to all outreach products as well as information on the project and permafrost in general. The most popular items were the research blogs that introduced the science done within the project directly from the field. These blogs regularly recorded 10 000 hits or more and directed vast amount of general public to the website.

The project partners presented the science done within the project in all major international scientific gatherings. The final policy-maker communication took place at the 2015 Arctic Circle assembly (www.arcticcircle.org) in which the PAGE21 organized a “Permafrost in the 21st century” plenary session. The plenary speakers included the project co-coordinators Hugues Lantuit and Julia Boike from AWI and Post Doctoral research fellow Sarah Chadburn from the University of Exeter. With over 1900 participants in the 2015 Assembly from over 50 countries the Arctic Circle is one of the largest gatherings in the world discussing Arctic issues.

The PAGE21 young researchers’ activities were gradually developed into a very successful inter-disciplinary cooperation in international fora beyond the European Union. The young researchers organized a series of workshops in which they focused on field scientist and modeler interaction and site visits when possible. The YRs emphasized throughout the project the need of sharing knowledge between disciplines while creating opportunities to see and try out different field methods used in permafrost research in hands-on exercises.

The PAGE21 YR worked successfully together with their Canadian counterpart within the ArcticNet funded ADAPT project. Further, together with participants from ADAPT, Permafrost Young Researchers Network (PYRN) and Association of Polar Early Career Scientists (APECS) they organized a Permafrost Young Researchers Workshop, which was held in conjunction with the 4th European Conference on Permafrost (EUCOP4) in Evora Portugal in 2014. The workshop included approximately 100 European as well as international early career permafrost scientists and engineers aiming to build interdisciplinary knowledge on how the Arctic and Antarctic permafrost regions play a key role in the Earth System. The workshop was mentored by IASC, which is leading the process towards the 3rd International Conference on Arctic Research Planning (ICARP III) and the International Permafrost Association (IPA), which is leading the permafrost related issues within ICARP III. Several members of IASC working groups (Cryosphere and Terrestrial) acted as mentors in this effort. The outcomes of the workshop were published in a peer-reviewed journal and communicated directly to IASC and IPA as an YR strategy for the Third International Conference on Arctic Research Planning - ICARP III.

PAGE21 Foreground

The main project foreground is the general advancement of knowledge on physical permafrost processes and their implementation into the three European based global climate models.

The new SOC inventories have contributed to the state-of-the-art Northern Circumpolar Soil Carbon Database (NCSCD), which had a paucity of data for the Eurasian and High Arctic sectors. With the data on SOC quantity and quality the project partners are able to develop pragmatic classes for upscaling potential SOC decomposability to northern circumpolar scales, using simple soil horizon type and landscape unit criteria, and identify vulnerable permafrost carbon pools. This is a significant step
in order to be able to assess the full permafrost carbon-climate feedback under global warming.

Furthermore, the project obtained new data on greenhouse gas fluxes and carbon fluxes from permafrost soils and ecosystems. These systems are under pressure as a result of climate change and the greenhouse gases released from thawing permafrost and changes in the greenhouse gas balance of these ecosystems may exacerbate global warming.

This foreground may be exploited in the very near future for validation and further development of the land surface components in climate models, in two ways: by providing more and better validation data and by enhancing process knowledge that may lead to improvements of the models. Additionally, the data may be used in the future for fostering more sustainable use of permafrost areas. For instance, the project has shown that greenhouse gas emission may increase strongly after tundra vegetation disturbance.

The potential impact is an improvement of understanding and modeling of the Arctic carbon feedback and carbon cycle feedbacks to climate change in general. This impact is difficult to quantify exactly, but a reduction of the uncertainty in these feedbacks as noted in the latest IPCC AR5 report can be expected.

The data have been made available through the PAGE21 web portal and are available through the NCSCD, European Fluxes and Pangaea databases. Several research papers are being prepared.

Further monitoring of greenhouse gas and carbon fluxes from permafrost is very urgently needed, given the rapid changes that are occurring in the Arctic, both the impact of climate change and the rapid pace at which human activities increase. In particular, the large areas of ice-rich lowland permafrost need a more dense observation network and more facilities should be available to obtain year-round flux data and meteorological observations.

The role of lakes in the Arctic landscapes GHG budget has been debated for the last couple of decades. The latest PAGE21 results with regards the budget are one of the most comprehensive. Full year GHG budgets for the Arctic area are rare and the present understanding gives an increased certainty in the scientific understanding of the importance of thawing of permafrost on the GHG exchange. Data have been disseminated to the European Fluxes database database and are open to researchers and public. The data will advance the understanding of the GHG feedback mechanisms of the arctic area, while further research is still needed to understand the impacts in other ecosystem types and for e.g. with regards radiation.

Nest-DNDC model was developed to improve simulations of carbon cycling in northern arctic regions especially by implementing permafrost actions into the model and improving plot-scale simulations (fine-scale modelling; results are upscaled by detailed information on the landscape). The purpose is to better predict future climate-permafrost feedbacks on a plot scale.

The Nest-DNDC is open source software and can be exploited by downloading it from the internet. It can be used by modellers to compare different process based models or ESM outputs, to develop permafrost schemes in models or by researchers using their own datasets. Further research is necessary, since the model is under constant development to include especially permafrost thawing and wetland dynamics.

Several remote sensing products were developed within the project to support the climate model validation. Improved version of the downscaling procedure based on Orchidee model was introduced together with an improved forcing files based on Land cover CCI map. Improved methodology for SSM/I LSTs inversion was established as well as a method for correction of ASCAT derived soil moisture in areas with significant water fraction. Enhanced remote sensing method for upscaling of soil organic carbon (100cm) from C-Band SAR together with an improved version of circumpolar SOC map was produced. A method for land surface classification in tundra regions (especially wetlands) from C-Band SAR was developed, enabling the creation of a new circumpolar wetland map.

These developments are available for the scientific community immediately and will provide an enhanced validation capability for the global climate models.

The three main European Earth System Models involved in PAGE21 were developed during the project lifetime to take into account permafrost-related processes that had not been properly represented in the past CMIP inter-comparisons (CMIP is the
international model inter-comparison project, coordinated by the World Climate Research Programme WCRP, that form the basis of quantitative climate projections presented, among others, in the IPCC reports).

The modeling groups involved in PAGE21 will use these improved climate models in all future large-scale climate assessments and coordinated climate projection exercises, most notably in future CMIP exercises (but probably not yet entirely in CMIP6). Future developments are required concerning thermokarst, interactions between fires and permafrost, interactions between vegetation and permafrost, spatial heterogeneity, peatland processes, etc.

The expected impact of this work is substantial, in particular on future assessments of the land-surface carbon feedback with global climate models. In the most recent IPCC assessment, this feedback was assessed as positive (which it certainly is) although the insufficient representation of permafrost carbon in global climate models suggested otherwise (i.e. expert knowledge was used to “override” erroneous model projections, which will not be required in future IPCC-style assessments).

A database under the auspices of PAGE21/GTN-P (ISSN 2410-2385) was designed and programmed. It is a comprehensive database for permafrost monitoring parameters where permafrost researchers and other stakeholders can download data and detailed metadata for a specific site or region of optional size in the entire terrestrial permafrost zone. Within the data management system an automated calculation of the depth of zero annual amplitude in the NetCDF file format is implemented to serve as an additional variable for global models.

In connection to the database, PAGE21 online Data Outputs Catalogue was created. It lists and gives access to all data products and associated reports from PAGE21 collected and stored in the GTN-P Database, PANGAEA and the European Fluxes Database.

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