

Permafrost and Changing Climate: The Russian Perspective

The permafrost regions occupy about 25% of the Northern Hemisphere's terrestrial surface, and more than 60% of that of Russia. Warming, thawing, and degradation of permafrost have been observed in many locations in recent decades and are likely to accelerate in the future as a result of climatic change. Changes of permafrost have important implications for natural systems, humans, and the economy of the northern lands. Results from mathematical modeling indicate that by the mid-21st century, near-surface permafrost in the Northern Hemisphere may shrink by 15%–30%, leading to complete thawing of the frozen ground in the upper few meters, while elsewhere the depth of seasonal thawing may increase on average by 15%–25%, and by 50% or more in the northernmost locations. Such changes may shift the balance between the uptake and release of carbon in tundra and facilitate emission of greenhouse gases from the carbon-rich Arctic wetlands. Serious public concerns are associated with the effects that thawing permafrost may have on the infrastructure constructed on it. Climate-induced changes of permafrost properties are potentially detrimental to almost all structures in northern lands, and may render many of them unusable. Degradation of permafrost and ground settlement due to thermokarst may lead to dramatic distortions of terrain and to changes in hydrology and vegetation, and may lead ultimately to transformation of existing landforms. Recent studies indicate that nonclimatic factors, such as changes in vegetation and hydrology, may largely govern the response of permafrost to global warming. More studies are needed to better understand and quantify the effects of multiple factors in the changing northern environment.

CLIMATE, PERMAFROST, AND CHANGE

The Arctic has shown the most rapid rate of warming in recent years and continues to be a climate-change hot spot (1). The Arctic is extremely vulnerable to projected climate change, with major impacts anticipated in physical, ecological, sociological, and economic factors (2). Many such impacts have already been detected and are likely to continue in the future (3). This paper focuses on the impacts changing climate may have on permafrost.

Although in the public imagination the term “permafrost” is often associated with massive ice buried under the ground, it does not imply the presence of the frozen water. Frozen ground may be “dry”; the term “permafrost” refers to any subsurface materials that remain below 0°C for at least two consecutive years. Regions where permafrost underlies all or part of the ground surface occupy about 25% of land area in the Northern Hemisphere, of which about 16.7 million km² is located in northeastern Eurasia and 10.2 million km² in North America (4). Permafrost is divided into continuous, discontinuous, and sporadic zones depending on its areal continuity. Continuity of permafrost is governed by many factors, among which are the climate, presence of large water bodies, snow cover, vegetation,

soil conditions, and topography. Most commonly used classifications define permafrost zones as regions where more than 90%, 50% to 90%, and less than 50% of land is underlain by the frozen ground (5). Permafrost zones differ in ground temperature, depth of seasonal (summer) thawing, and mechanical strength of the frozen ground. Mean annual ground temperature is typically between –8 to –13°C in the northernmost zone of continuous permafrost, –3 to –7°C in the discontinuous zone, and 0 to –2°C in the southern sporadic zone. Permafrost thickness varies from as much as 1500 m in parts of Siberia and 740 m in northern Alaska to less than a meter in the southern zone, and is typically between 100–800 m, 25–100 m, and 10–50 m in the continuous, discontinuous, and sporadic zones, respectively.

The uppermost layer of seasonal thawing, called the “active layer,” varies from several decimeters on the Arctic coast to a few meters in the sporadic permafrost zone. The active layer is shallower in the presence of organic soil and lower nonvascular vegetation, particularly in combinations of peat and mosses or lichens. In summer, the unfrozen organic layer has very low thermal conductivity and reduces the heat flux to the ground, thus preventing permafrost from thawing. This effect is much more pronounced in dry soils. In winter conductivity of the frozen organic layer is much higher, and does not affect the heat flux to the atmosphere as effectively as it does during the warm period of the year. Therefore, the net effect of the organic layer and nonvascular vegetation is to lower the permafrost temperature and decrease the seasonal thaw depth.

Permafrost zones are associated with different landform and vegetation classes, ranging from the polar desert populated by the few lower vegetation species in the far north of the continuous zone, to shrublands and boreal forest in the southern sporadic zone. Tundra occupies most of the permafrost regions. Changing climate will cause shifts in vegetation zones, which will have impacts on permafrost through changes of the thermal conductivity of the organic/vegetation layer. Controlled long-running field experiments simulating climatic warming at several sites throughout the circumpolar Arctic indicated the tendency towards gradual replacement of lichens and mosses with taller vascular plants that have higher thermal conductivity and better accumulate snow (6, 7). Changes in the abundance and range of the vegetation species may thus control the climate-permafrost interaction.

PERMAFROST OBSERVATIONS

Climatic change, together with the other changing environmental factors, is likely to cause warming, deeper seasonal thawing, and shrinking of permafrost. Direct observational data about the long-term response of permafrost to climatic variations are not available except for a few locations. The longest record of permafrost temperature is available in Yakutsk from the 116.4-m-deep well. In 1848 it was instrumented and used for geothermal observations (8). Russian researchers in the 19th century used data coming from these observations to study geothermal heat conduction in frozen ground and to evaluate the extent and thickness of permafrost in Siberia. Already at that time researchers noted that “permafrost obviously depends

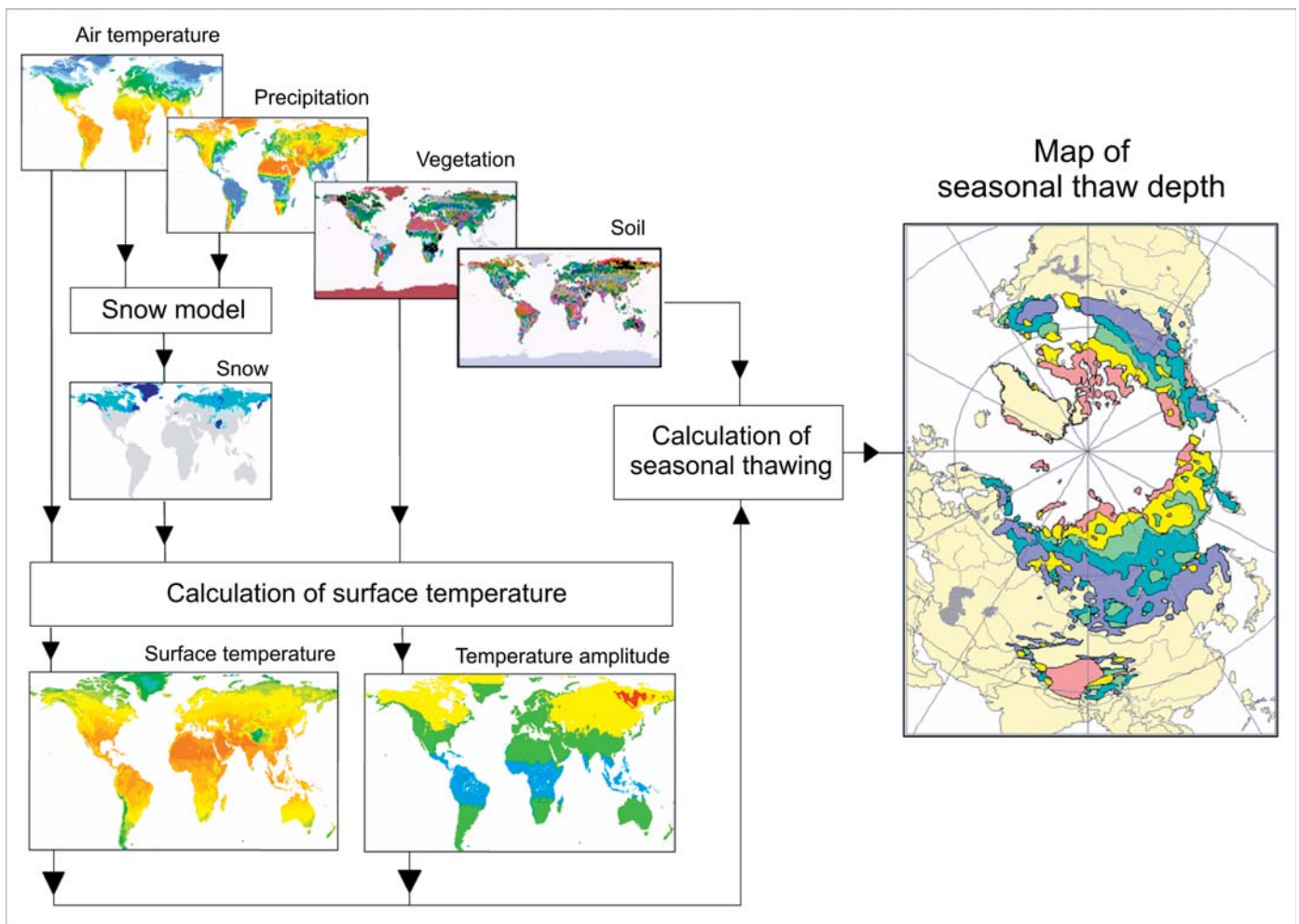


Figure 2. Computational design of the hemispheric-scale permafrost model.

ing five particular scenarios is the conclusion of the Arctic Climate Impacts Assessment (ACIA) report that these GCMs represent the observed modern climatic changes in the circumpolar Arctic region better than others (29).

The goal of our study was threefold: to evaluate the sensitivity of the permafrost model to the forcing data and estimate the range of uncertainty in predicting key permafrost parameters associated with climatic scenarios; to evaluate the potential risks to infrastructure in Russian permafrost regions, and construct a predictive hazard map for the mid-21st-century climatic conditions; and to estimate the contribution of the Russian permafrost regions to the global radiative forcing through enhanced emission of methane from the wetlands.

The permafrost model has been detailed in preceding publications (30, 31). Computational design is illustrated in Figure 2. The model requires only two input climatic parameters, mean monthly averaged air temperatures and precipitation, which are used in the snow model to calculate the winter-average snow depth. Snow, vegetation, and soil data are used in the model to calculate the annual-mean and the amplitude of the soil surface temperature, and the maximum depth of seasonal thawing (active-layer thickness). The model is applied repeatedly at each node of the $0.5^\circ \times 0.5^\circ$ lat/long grid for which soil, vegetation, and baseline climatic data are available. GCM-based climatic scenarios have lower resolution, approximately 1.25° lat/long, and in the predictive calculations the permafrost model was forced with high-resolution baseline climatology overlaid with the projected changes of monthly temperatures and precipitation from the nearest GCM node.

PERMAFROST PROJECTIONS

We used the model to calculate the displacement of permafrost boundaries and changes of active-layer thickness under future climatic conditions. Projected by 2030, 2050, and 2080, reduction of the near-surface permafrost area in the Northern Hemisphere under five climatic scenarios is shown in Table 1. Partitioning into continuous, discontinuous, and sporadic zones was made using the conventional frost index-based approach introduced by Nelson and Outcalt (32).

Results vary substantially among the climatic scenarios, indicating that uncertainties in the forcing data are large. The "median" GFDL-based scenario predicts the reduction of the total near-surface permafrost area by 11%, 18%, and 23% by 2030, 2050, and 2080, respectively. The projected contractions of the continuous near-surface permafrost zone for the same times are 18%, 29%, and 41%, respectively. Among the five selected climatic scenarios, the two end-members are the ECHAM-based scenario, which predicts the largest contraction of the area occupied by near-surface permafrost (29% by 2050), and the CCC scenario that predicts only modest changes (13% reduction by 2050). Projections obtained with the HadCM3 and NCAR scenarios are close to the "median."

Results presented in Table 1 should be interpreted with caution; by the designated time thawing may only affect the upper permafrost layer, while deeper ground layers may still remain frozen. In the continuous zone the major effect will be the deepening and areal expansion of the unfrozen "islands" that exist under the large rivers and lakes. Even in the southern sporadic permafrost zone complete thawing of permafrost layer

Table 1. Projected reduction of the near-surface permafrost area in the Northern Hemisphere by 2030, 2050, and 2080 under climatic scenarios from five GCMs.

GCM	Million km ² (% present-day value) of:											
	Total permafrost value			Continuous permafrost area								
	Total	2030	2050	2080	2030	2050	2080					
CCC	24.24	23.64	21.99	10.69	10.06	9.14	89%	87%	81%	86%	81%	74%
HadCM3	24.45	23.07	21.36	10.47	9.44	7.71	90%	85%	78%	84%	76%	62%
GFDL	24.11	22.38	20.85	10.19	8.85	7.28	89%	82%	77%	82%	71%	59%
NCAR	23.72	21.94	20.66	9.83	8.19	6.93	87%	81%	76%	79%	66%	56%

10 m thick or thicker may take several decades under the sustained climatic warming because of the latent heat involved in phase changes of water.

Increases in the depth of seasonal thawing could be a relatively short-term reaction to climatic warming, since it does not involve any lags associated with the thermal inertia of climate/permafrost system. Maps in Figure 3 show the mid-21st-century projections of the active-layer changes in Northern Eurasia under three of five selected scenarios. These maps have been constructed using high generalization of permafrost, soil, and vegetation properties over 0.5° by 0.5° grid cells. Because of the effects of local environmental factors, including topography and vegetation variations, seasonal thaw depth is characterized by pronounced spatial and temporal variability (33), so the real conditions at particular locations may be different from those obtained here. To minimize the uncertainties associated with the subgrid effects of local factors projected changes of the active-layer thickness were expressed as a fraction of the modern norm. The recent study by Anisimov and Belolutskaja (18) indicated that climate-induced changes of vegetation may largely offset the effects of warming in the northernmost permafrost regions on one hand, and lead to enhanced degradation of sporadic and discontinuous permafrost on the other. However, the results presented here were obtained under the assumption that the vegetation does not change in the course of warming because realistic scenarios of such changes are not available and are yet to be developed.

Despite their limitations, the maps provide a broad picture of continental-scale changes of seasonal thaw depth under changing climate conditions that are generally consistent with results obtained in more detailed regional studies at selected locations in Siberia. There is general consensus that the seasonal thaw depths will increase by more than 50% in the northernmost permafrost locations, including much of Siberia and the Far East; and by 30% to 50% in most other permafrost regions.

IMPLICATIONS FOR PREDICTIVE HAZARD MAPPING

Serious concerns are associated with the impacts thawing permafrost may have on the engineered structures built upon it (34, 35). This problem is particularly important for Russia (36). More than 60% of the Russian territory is located in permafrost regions. Several large cities (Yakutsk, Noril'sk, Vorkuta) with populations of more than a hundred thousand and large river ports are built upon permafrost. The ability of permafrost to support buildings upon it (the bearing capacity) decreases with warming. The foundations are designed with a construction-specific safety factor, which in the practice of the

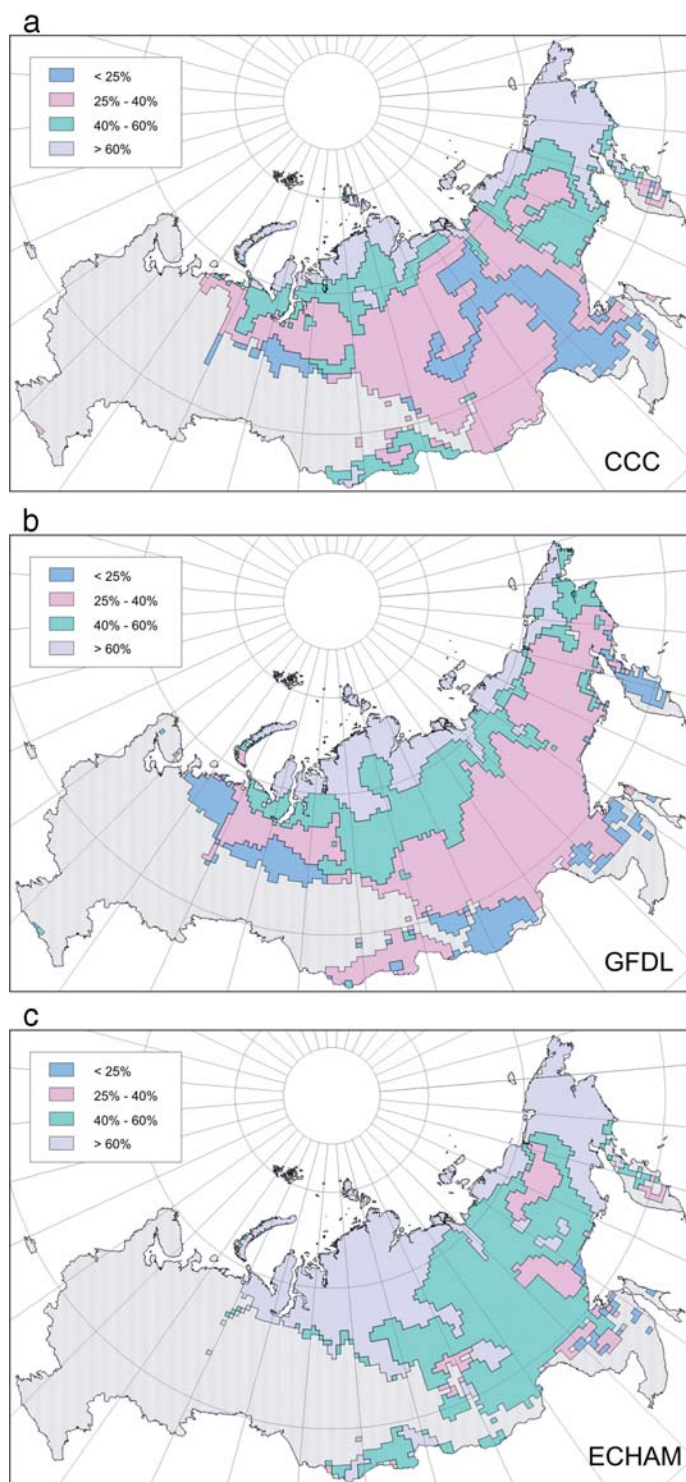


Figure 3. Projected by the 2050 changes of the active-layer thickness in northern Eurasia, relative to present-day simulations, based on forcing from three different global climate models: (a) CCC (Canadian Climate Center) scenario; (b) GFDL scenario; (c) ECHAM scenario. Full documentation of climatic scenarios is available on the Internet (<http://ipcc-ddc.cru.uea.ac.uk/> and <http://igloo.atmos.uiuc.edu/IPCC/>).

cold-region engineering varies from 5% to 60% with respect to the bearing capacity, and is typically 20% for the most of the residential buildings in the Russian northern cities. Warming of permafrost and decrease of the bearing capacity beyond the safety range may seriously affect the constructions upon it, ultimately leading to damage.

A survey in the Russian northern cities indicated that in 1992 the percentage of damaged buildings was 10% in Norilsk, 22% in Tiksi, 35% in Dudinka and Dikson, 50% in Pevek and



Figure 4. Section of the residential building in town Cherskiy, lower Kolyma River valley, collapsed in June 2001 as a result of weakening of the foundation built upon permafrost. Although there is still a debate whether the climatic change or improper management of the construction caused warming and thawing of the frozen ground underneath the building, the accident illustrates the potentially detrimental impact of permafrost degradation, whichever is the factor that caused it. Photo: by V.E. Romanovskiy.

Amderma, 55% in Magadan, 60% in Chita, and 80% in Vorkuta (37). In the period from 1990 to 1999 the rate of reported damage to buildings increased by 42% in Norilsk, 61% in Yakutsk, and 90% in Amderma. The picture in Figure 4 illustrates the effect of permafrost changes on residential building in the Russian northern town Cherskiy located in the valley of the lower Kolyma River. There is still a debate whether the climate change or improper design of the construction, leaking sewage, and other similar anthropogenic influences are responsible for the current dramatic situation in the Russian North. Obviously, there is a combination of the acting factors, but the buildings are ultimately damaged as a result of the weakening of permafrost underneath them. As global warming continues to evolve, it may produce similar impacts on structures throughout the circumpolar permafrost regions, even under appropriate practices of environmental management.

The Russian North is industrially well developed. In the context of changing climate, the infrastructure of the oil and gas industry is of particular concern, because of its economic importance and potential environmental threats associated with oil spills (38). Extracting facilities, pump stations, and pipelines are affected by the geomorphological processes that involve

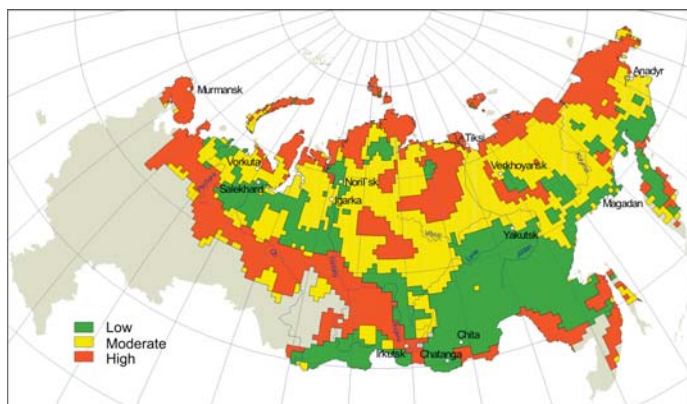


Figure 5. Predictive permafrost hazard map for Russia. The map was constructed using the GFDL climatic scenario for 2050. Permafrost area is split into zones with low, moderate, and high potential hazard to the structures built on permafrost.

various forms of mass movement of thawing material and ground settlement due to thermokarst. Many such processes have been favored under the warmer climatic conditions of the last decade. The annual number of accidents on the 350 000-km-long network of pipelines in West Siberia totals 35 000 (39). About 21% of the reported accidents are caused by mechanical damage to the pipelines as a result of increased strength, deformation, and weakening of the foundations anchored in permafrost, and are thus very likely to be related to climatic change, warming, and thawing of the frozen ground (40).

Destructive impacts of thawing permafrost on human infrastructure are not necessarily abrupt; in many cases they evolve gradually and may be predicted probabilistically using permafrost scenarios. In our study we used a methodology based on the geocryological hazard index, I_G , which is the combination of the projected change in active-layer thickness, ΔZ_{al} , expressed in relative units with respect to modern norm, and the volumetric ground ice content, V_{ice} , (34–36):

$$I_G = \Delta Z_{al} \cdot V_{ice} \quad \text{Eq. 1}$$

We used projections of active-layer thickness and data from the map of permafrost and ground ice conditions (5) to calculate the hazard index. The predictive hazard map in Figure 5 was constructed using the “median” GFDL climatic scenario for 2050 and is focused on the Russian permafrost regions.

Regions on the map are partitioned into areas with low, moderate, and high potential hazard to the structures built upon permafrost. The southern zone of high hazard potential extends continuously from the southwestern limit of permafrost on the Kola Peninsula through Komi Republic and Tumen region to Lake Baikal. The southeastern part of the map is patterned indicating high hazard potential in close proximity to the cities Chita, Blagoves'chensk, Komsomolsk-na-Amure, over most of the Japan seacoast, and at selected locations on Sakhalin and Kamchatka. Here, high potential threats are associated with the projected thawing of sporadic permafrost, most of which may disappear in the near-surface layer by the middle of the century. Such changes are particularly detrimental to the roads, pipelines, and rail tracks traversing the permafrost islands. Uneven ground settlement due to thermokarst and soil erosion may lead to dramatic distortions of landscape and badly affect the engineered structures.

The northern zone of high hazard potential includes the Russian Arctic coast from the Kara Sea on the west to the Chukchi Sea on the east. River terminals in Salekhard, Igarka, Dudinka, and Tiksi fall within this zone. It spreads deep into the continent in central Siberia and Yakutia. These regions are underlain by continuous permafrost, which will not change noticeably in areal extent; the main effect will be warming and deeper seasonal thawing of the frozen ground, which may exceed the safety limits incorporated in the design of the constructions. Such changes are potentially dangerous for the preexisting structures, whereas the design, foundations, and managing practices of the newly constructed buildings may be adjusted to changing permafrost properties. Particular concerns are associated with the Yamal Peninsula, which was periodically flooded during the ocean transgressions in the geological past. Because of the presence of salt in the deposits the thawing/freezing point is lowered. Permafrost here is in delicate balance with climate and may become unstable even under a slight climatic variation.

Most of the central part of the Russian permafrost falls into the zone of moderate hazard potential, whereas large areas in southern Yakutia and in central Siberia between the Ob and Yenisey Rivers will have low susceptibility to climate-induced permafrost hazards.

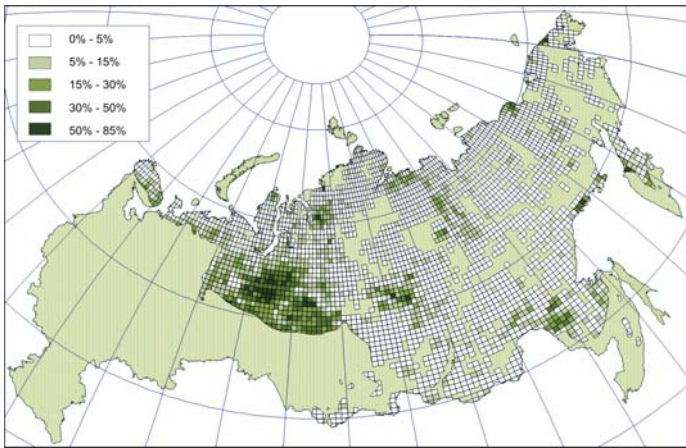


Figure 6. Fraction of land area occupied by wetlands in the Russian permafrost regions. Data presented in $0.5^\circ \times 0.5^\circ$ lat/long grid nodes have been calculated using digital geographically referenced contours of 59 846 Siberian wetlands from the database of the Russian Hydrological Institute in St. Petersburg.

CONTRIBUTION OF THAWING PERMAFROST TO GLOBAL RADIATIVE FORCING

Thawing permafrost has strong potential to affect the global climate system acting through release of greenhouse gases to the atmosphere. Arctic soils contain approximately 455 Gt C, or 14% of the global soil carbon (41). Deeper seasonal thawing and higher soil temperatures will enhance decomposition of the organic material and emission of greenhouse gases, whereas longer growing seasons and northward movement of productive vegetation are likely to increase photosynthetic carbon uptake (42). Currently, the circumpolar permafrost regions have near-zero annual balance of carbon in the form of CO_2 (43). However, they effectively contribute to the global radiative forcing converting atmospheric carbon from CO_2 to methane, which has a much stronger greenhouse effect (44). The atmospheric concentration of methane is increasing by approximately 1% annually. In the last 250 y, warming due to changes of CH_4 atmospheric content was up to one-third of the effect of rising CO_2 concentration (45). In this regard, the Arctic wetlands are of particular importance. They occupy almost 2 million km^2 in the circumpolar region, contain about 50 Gt C, and because of the high groundwater levels, favor the production of methane rather than carbon dioxide in the anaerobic carbon-rich soil layer (46). Although the processes leading to the emission of methane from the thawing wetlands are relatively well studied, estimates of their contribution to the global radiative forcing under the projected-for-the-future climatic conditions are yet to be obtained. Here, we present the regional estimate for wetlands in the Russian part of the Arctic.

The sparse data on methane fluxes from the Russian permafrost regions were used to validate a soil carbon model detailed in the preceding publications (46, 47). In the context of global climatic warming two major factors, ground temperature and the depth of seasonal thawing, are likely to have major controls over the potential changes of methane fluxes. The highly generalized semiempirical equation linking these parameters has the following form (47):

$$J_2/J_1 = \exp 0.1(T_2 - T_1) \sqrt{Z_{th2}/Z_{th1}} \quad \text{Eq. 2}$$

Here J_2 and J_1 designate the summer-mean methane fluxes projected under future and current climatic conditions; T_2 and T_1 , and Z_{th2} , Z_{th1} represent mean summer ground temperature and depth of seasonal thawing, respectively.

We used the digital geographically referenced contours of 59 846 Siberian wetlands from the database of the Russian

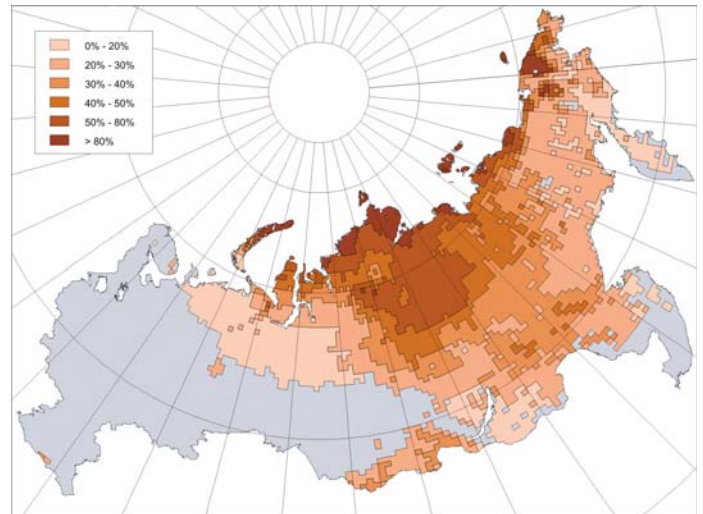


Figure 7. Projected changes of methane fluxes from the seasonally thawing wetlands in Russian permafrost regions. Climatic scenario for the mid-21st century is based on results from GFDL model. Changes are expressed in percentage from the modern norm.

Hydrological Institute to calculate the percentage of the land area they occupy in each node of $0.5^\circ \times 0.5^\circ$ lat/long regular grid spanning the permafrost region (47). Such a “wetland mask” for the Russian Arctic is shown in Figure 6. Seasonal thaw depth, Z_{th} , and temperature of peat, T , for the current and projected-for-the-future climatic conditions were calculated using the permafrost model and substituted into Eq. 2 to evaluate the relative changes of methane fluxes. Results for the mid-21st-century GFDL climatic scenario are presented on the map in Figure 7.

The conclusion apparent from comparison of the maps in Figures 6 and 7 is that the largest relative increase of methane emission, by 50% or more, is expected along the Arctic coast, in Central Siberia and Yakutia. Wetlands are sparse here, whereas in West Siberia the projected flux changes are below 20%. Given that most of the wetlands are located in this region, it is unlikely that by the middle of the century the total methane emission from the Russian permafrost will increase by more than 25%–30%.

The potential contribution of the projected enhanced emission of methane to the global radiative forcing is illustrated

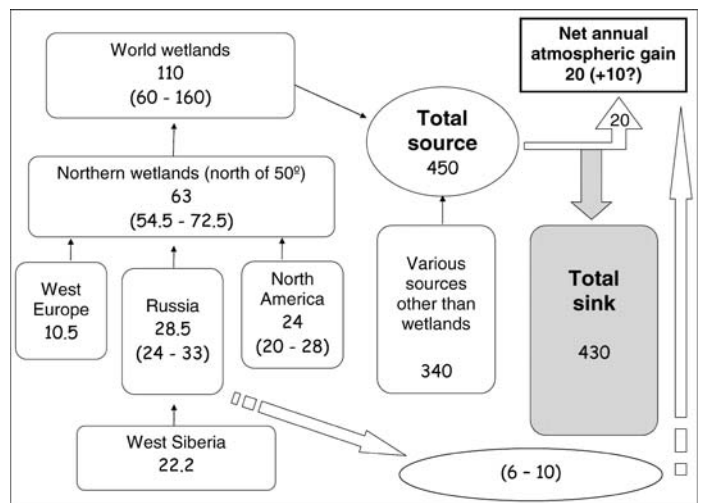


Figure 8. Contributions from regional sources to the global balance of the atmospheric methane. Numbers indicate millions tons of CH_4 per year. Projected by the mid-21st-century, an increase of the contribution from the Russian frozen wetlands by 6–10 million tons is comparable with the modern net annual atmospheric gain of methane (20 million tons) and is likely to affect the global radiative balance.

in Figure 8. The data on this diagram were collected using various published estimates, and characterize the current balance between global sources and sinks of methane (47). According to these data, the net annual atmospheric gain is about 20 million tons. Wetlands in the Russian part of the Arctic give 24–33 million tons to this global balance and by the middle of the century are likely to increase their contribution by 6–10 million tons. In the hypothetical and highly improbable case of the sinks being unchanged, this extra emission may shift the current global balance of methane by 50%, ultimately leading to a much faster rise of the atmospheric CH₄ concentration and significant enhancement of the radiative forcing. In reality, however, factors that have not been taken into account in our analysis may substantially offset this estimate. Besides the changing sinks, these are the hydrological conditions that govern the balance between methane and carbon dioxide emissions. Better drainage and enhanced evapotranspiration may lower the water table and improve soil ventilation, ultimately shifting the balance in favor of CO₂ rather than CH₄ production. The opposite case of soil wetting, from increased precipitation and permafrost thawing, will increase fluxes of methane relative to carbon dioxide from the active layer and thawing permafrost. More studies are needed to predict and quantify such processes in detail (48).

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