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GEOPHYSICS

Model Assessments of Organic Carbon Amounts Released from Long-Term Permafrost under Scenarios of Global Warming in the 21st Century

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The general increase in the surface temperature recorded in recent decades, which is especially high at high and mid-latitudes, and variations in the amount of precipitation influence the thermal and hydrological regime of the planet. At the end of the 20th century, the rate of annual mean temperature increase in long-term permafrost rocks was as high as 0.03°C per year based on observations in some land regions of the Northern Hemisphere [1]. It may increase in the 21st century up to 0.05°C per year based on the results of simulations using global climatic models [2]. As a result, we can expect an increase in the depth of the active layer with inclusion of organic matter into the biogeochemical cycle in the thawed permafrost, which can lead to the emission of greenhouse gases into the atmosphere. Degradation of surface long-term permafrost rocks facilitates release of greenhouse gases conserved in them and an increase in the positive feedback between the cryolitic zone and the atmosphere if the expected climate variations occur [3, 4].

In this work, we estimated the amounts of carbon that could be released from the surface long-term permafrost rocks as a result of their degradation by the end of the 21st century under the least aggressive (RCP 2.6) and most aggressive (RCP 8.5) anthropogenic scenarios [9]. These estimates were made on the basis of the results of thermal process modeling in the cryolitic zone using the dynamic model of heat and moisture transport in the ground (DMPG) [2, 5] and the data of resources and vertical distribution of carbon in the soil [6–8]. The monthly mean parameters of atmospheric forcing in the DMPG were specified from simulations using the global climatic models within the Coupled Model Intercomparison Project, Phase 5 (CMIP5) international project, including the calculations using the CSIRO–Mk3–6.0, GISS–E2–R, MIROC5, and IPSL–CM5A–LR models [10]. In the numerical simulations using the DMPG up to a depth of 13.5 m, the distance between the vertical model levels varied from 5 cm in the upper 10 to 50 cm at the lower boundary. In the permafrost regions, we specified the spatial boundaries of three characteristic types of vegetation (tundra, boreal forest, and steppe, see http://daac.ornl.gov/). The vertical distribution of the relative content of carbon in each type of vegetation was specified on the basis of the data of observations [7]. In the vertical distributions used in this work, the maximum carbon concentration was located in the upper 20 cm of the soil with a further exponential decrease in the carbon content with depth [7, 11].

The organic carbon deposits in the permafrost regions of the Northern Hemisphere, which are estimated at approximately 1.7 billion tons [4], exceed more than twice the total amount of carbon in the atmosphere [12]. More than one billion tons of carbon is deposited in the upper soil layers up to three meters thick [4]. Organic matter can accumulate not only in swamp ecosystems (approximately 0.3–0.5 billion tons [4, 13]) but can accumulate in the column of permafrost soils under the influence of cryogenic mass exchange processes and frost retinization [14].

The range of organic matter density in the upper one-meter layer of soils in the ecosystems of Siberia, Alaska, Canada, and Tibet based on the data of instrumental observations is quite wide from 2–8 [6] to 9–14 [7] and 4–20 kg C m^{-2} [11]. An even wider range of organic matter density values from 5 to 95 kg C m^{-2} in the upper 90 cm of soil was obtained in forest–tundra ecosystems of Siberia [15]. In this relation, we used in our simulations three versions of carbon density in the upper one-meter soil layer:

spatially distributed data [6] (numerical experiment Cs–1);

separate values for each of the three types of vegetation (14 kg C m^{-2} for tundra, 9 kg C m^{-2} for boreal

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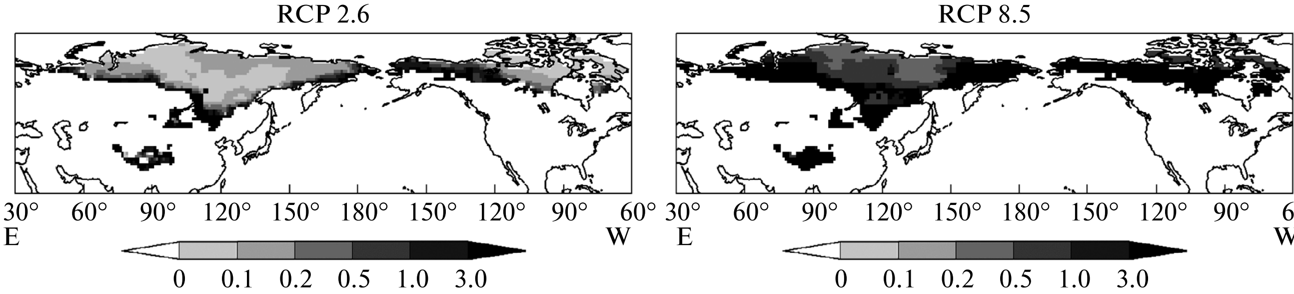

Fig. 1. Variations in the depth of the active layer (m) in the cryolitic zone of the Northern Hemisphere by 2090–2099 compared to 2001–2010 under anthropogenic scenarios RCP 2.6 and RCP 8.5 averaged over the ensemble of models.

forests, and 12 kg C m^{-2} for steppe) according to [7] (experiment Cs–2);

an equal value of 26 kg C m^{-2} for the entire territory of permafrost ground distribution [8] (experiment Cs–3).

We also took into account that the organic matter content in the soil layers below 3 m is small compared with the overlying layer [4, 7, 8]. An increase in the thickness of the melt layer greater than 3 m (for example when a talik develops) influences the total carbon content in the melt layer only slightly. The results of calculations of the depth of such a layer and the grid data on the deposits of carbon in the soil and the location of the boundaries of vegetation types were reduced to one grid with a spatial resolution of 1° by latitude and longitude.

According to the results of numerical simulations, the general increase in the depth of the melt layer occurs by the end of the 21st century in the regions of long-term permafrost rocks spreading under all tested scenarios of anthropogenic impact of the RCP family. Figure 1 presents the average variations of the model ensemble in the depth of the active cryolitic zone layer on the land of the Northern Hemisphere in the last decade of the 21st century relative to the first decade. Under the least aggressive anthropogenic scenario RCP 2.6, the layer of seasonal thawing in Western Siberia increases on average by 0.4 m, while in Eastern Siberia the seasonal melt layer deepens by 0.5 m. According to this scenario, the most significant increase in the melt layer by the end of the 21st century was obtained in Alaska and Tibet (an increase up to 0.8–1.4 m) and in the Baikal region (more than 2–2.5 m) where taliks are formed according to the results of modeling. The smallest increase in the seasonal melting depth (less than 10–15 cm) was obtained at high latitudes of North America and Western and Central Siberia. Under the most aggressive scenario of anthropogenic impact (RCP 8.5) at high latitudes of Eurasia and North America, the seasonal melt layer will increase by the end of the 21st century by 0.7–1.2 m, while the maximum increase in the thickness of the active layer (greater than 3–6 m) with the formation of taliks would be manifested at the southern boundary of the cryolitic zone in Western and Central Siberia, in the eastern part of Eastern Siberia and subarctic latitudes of North America.

It is worth noting that formation of taliks leads to an increase in the rate of melt layer depth increase. Such a character of variation in the depth of the active layer during formation of taliks is reported in [8]. According to the results of modeling reported in this paper, by the end of the 21st century (in the last two decades) the active layer at subarctic latitudes of Central Siberia can increase by 2–4 m.

The results of simulations provide evidence that by the end of the 21st century one should expect rapid degradation of surface long-term permafrost rocks in North America and Alaska. This feature is also characteristic of the last decades of the 20th century and the beginning of the 21st century based on the data of observations and model simulations [5].

Figure 2 presents the spatial distributions of carbon resources in the active layer of the cryolitic zone as a result of degradation of surface permafrost based on the model simulations under anthropogenic scenarios RCP 2.6 and RCP 8.5. In numerical experiment Cs–1 under the RCP 2.6 scenario, the release of organic matter from long-term permafrost rocks was found in the Baikal region, Tibet, and Alaska (Fig. 2a). By the end of the 21st century, approximately 7 Gt of organic carbon could have been released from permafrost. In this numerical experiment, an additional release of carbon was found under the RCP 8.5 scenario at high latitudes of western Siberia and individual regions of Eastern Siberia (Fig. 2a). The total amount of released organic carbon under this scenario is approximately 15 Gt.

In the CS–2 numerical experiment under the RCP 2.6 least aggressive anthropogenic scenario, release of carbon from the permafrost layer occurs in Tibet, at the southern boundary of the cryolitic zone in Western Siberia, in Transbaikalia, in eastern regions of Eastern Siberia, and in Alaska (Fig. 2b). According to the model estimates under this scenario, by the end of the 21st century, the total amount of organic carbon in melt ground would reach 20 Gt. Under the RCP 8.5

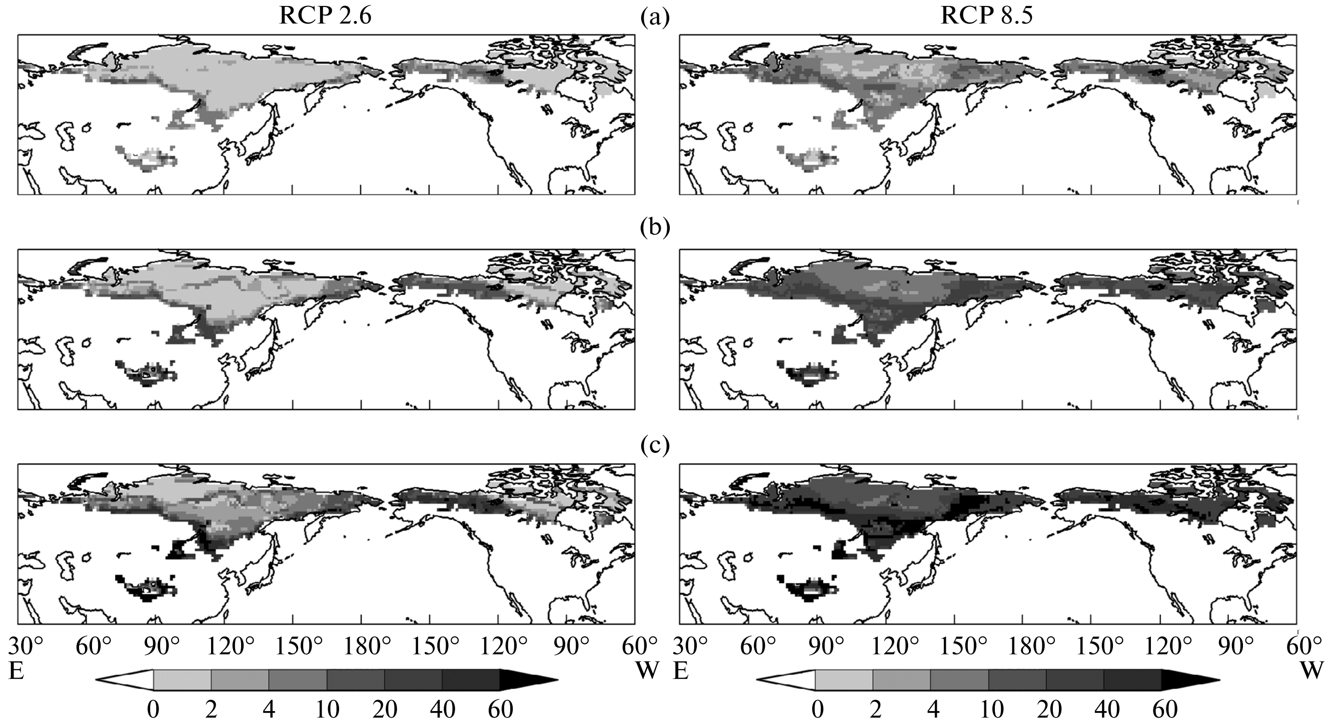

Fig. 2. Variations in the resources of organic carbon (Mt) in the active layer by 2090–2099 compared to 2001–2010 under anthropogenic scenarios RCP 2.6 and RCP 8.5 with different versions of carbon distribution in the upper layer of soil: Cs–1 (a), Cs–2 (b), and Cs–3 (c).

most aggressive scenario of anthropogenic impact, additional thawing of grounds will occur at high latitudes of Western Siberia and Canada. The total resources of liberated carbon up to the end of XXI century will make 44 Gt.

The maximum estimates of carbon resources that can participate in the biogeochemical cycle during thawing of surface long-term permafrost grounds were obtained in numerical experiment Cs–3. Under the RCP 2.6 scenario, the most significant release of carbon was found at subarctic latitudes of North America, in the Baikal region, and in Tibet (Fig. 2c). According to the model estimates under this scenario, 48 Gt C could have been released from permafrost by the end of the 21st century. Under the RCP 8.5 most aggressive scenario, the spatial structure of variations in the carbon resources in the active layer is similar to the one obtained from the results of numerical modeling in experiment Cs–2 with the maxima in the southern regions of the cryolitic zone of Eurasia and North America (see Figs. 2c, 2b). According to this scenario, the resources of organic matter released as a result of thawing of long-term permafrost ground by the end of the 21st century exceed 100 Gt C. Similar estimates of carbon resources, which can be transported to the atmosphere as a result of long-term permafrost thawing based on the results of simulations using climatic models (HadCM3, CCSM3, and MIROC3.2) under a moderate scenario of anthropogenic impact SRES–A1B are as high as 190 ± 64 Gt C by 2200 if the density of organic matter in the soil is constant [8].

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