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Thawing permafrost and methane emission in Siberia: Synthesis of observations, reanalysis, and predictive modeling

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Abstract Permafrost has been warming in the last decade at rates up to 0.39 °C 10 year^{-1}, raising public concerns about the local and global impacts, such as methane emission. We used satellite data on atmospheric methane concentrations to retrieve information about methane emission in permafrost and non-permafrost environments in Siberia with different biogeochemical conditions in river valleys, thermokarst lakes, wetlands, and lowlands. We evaluated the statistical links with air temperature, precipitation, depth of seasonal thawing, and freezing and developed a statistical model. We demonstrated that by the mid-21st century methane emission in Siberian permafrost regions will increase by less than 20 Tg year^{-1}, which is at the lower end of other estimates. Such changes will lead to less than 0.02 °C global temperature rise. These findings do not support the "methane bomb" concept. They demonstrate that the feedback between thawing Siberian wetlands and the global climate has been significantly overestimated.

Keywords Climate change · Methane emissions · Permafrost · Siberia

INTRODUCTION

Permafrost is a distinctive feature of high-latitude and high-altitude environments. It occupies 22.8 × 10^6 km^2 in the Northern Hemisphere and about 10.4 × 10^6 km^2 in Russia (Gruber 2012). Depending on areal continuity, permafrost is divided by coverage into continuous (> 90%), discontinuous (50–90%), sporadic (10–50%) zones, and isolated patches (< 10%). It is characterized by two parameters: mean annual soil temperature (T_s) at the top of permafrost and thickness of the uppermost layer of the seasonally thawing soil (active layer thickness, ALT). ALT plays multiple roles regulating the amount of accessible soil carbon, providing habitat to the roots of plants and governing the soil hydrology.

Historically, Russian theoretical and field studies played a pivotal role in shaping permafrost science, largely in association with the exploration of Siberia. The first temperature observations in the 116.4 m deep "Shergin well" in Yakutsk were made in 1837. Shiklomanov (2005) provided a sketch of 19th and early-20th century permafrost science in Russia. In 1953, the world's first department of geocryology was founded in Moscow State University, with focus on fundamental research, permafrost engineering, and modeling. In 1960, the Russian Academy of Science established what is now known as the Melnikov's Permafrost Institute in Yakutsk (East Siberia). Research in the institute was focused on permafrost monitoring, and on ALT and ground temperature observations in representative sites under natural and manipulated conditions such as experimental removal of snow, vegetation, and the organic layer. In 1991, the Earth Cryosphere Institute was established in Tumen in West Siberia with the primary goal of serving the needs of the northward-expanding oil and gas industry. Russian federal service on hydrometeorology (Roshydromet), which is responsible for the meteorological and hydrological network, holds the century-scale records of the daily ground temperature observations at standardized depths up to 3.2 m at 146 weather stations in the permafrost regions. As a result of these efforts, the base of practical and scientific knowledge and a large body of permafrost observations have accumulated in Russia long

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before international academic projects, such as the Circumpolar Active Layer Monitoring (CALM) and the Thermal State of Permafrost (TSP) temperature observations in boreholes came into existence (AWI 2019). Russian involvement in such scientific networking made all these Russian data available to the international community.

Despite recent improvements in the availability of field data through a dedicated web portal (AWI 2019), permafrost science remains data limited. Observations are sparse, uneven in space and over time, and do not capture the full range of climatic, edaphic, vegetation, and landscape variability. As demonstrated in Fig. 1, the largest number of T_s observations comes from boreholes, which are clustered and unevenly distributed between the permafrost zones. Of the total 384 Russian boreholes, 241 are located in the continuous zone around 27 hubs, 88 in the discontinuous (15 hubs), 25 in sporadic (8 hubs), and 9 in the isolated patches (5 hubs). Similarly, 68 CALM sites with ALT observations are clustered around 21 hubs with 57 sites in the continuous, 7 in the discontinuous, and 1 in the sporadic permafrost zones.

Recent studies have reported accelerating permafrost warming in the circumpolar Arctic in the last decade of up to $0.39 \pm 0.15\,°C\ (10\ \text{year})^{-1}$ in the continuous and $0.20 \pm 0.10\,°C\ (10\ \text{year})^{-1}$ in the discontinuous zones (Biskaborn et al. 2019). Rapid warming raises concerns about the fate of ecosystems (Hoffmann et al. 2019), impacts on infrastructure (Hjort et al. 2018), and carbon emissions (Schuur et al. 2015; Walter Anthony et al. 2018). The estimated amount of carbon in the Northern hemisphere permafrost is 1670–1850 Pg (Schuur et al. 2015; Christensen et al. 2017), of which about 1024 Pg is located in the upper 3 m soil layer (Tarnocai et al. 2009). Thawing of this layer may have potentially large impacts on the global climate through emission of greenhouse gases.

The goals of our study are two-fold: First, to analyze the modern permafrost dynamics under the changing climatic conditions, and second, to study the potential effect of methane emission from thawing Siberian wetlands on the global climate. This paper contributes to a series of studies on Siberian environmental change (Callaghan et al. 2021).

MATERIALS AND METHODS

We calculated modern air temperature and snow depth trends over the Siberian permafrost domain using the CRU TS v4.03 database (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/) and compared them with observed ALT and T_s changes. In this study, snow depth is approximated by the sum of precipitation in the cold months November–April. Using data from 146 weather stations (Fig. 1), we performed statistical analysis and evaluated the effect that

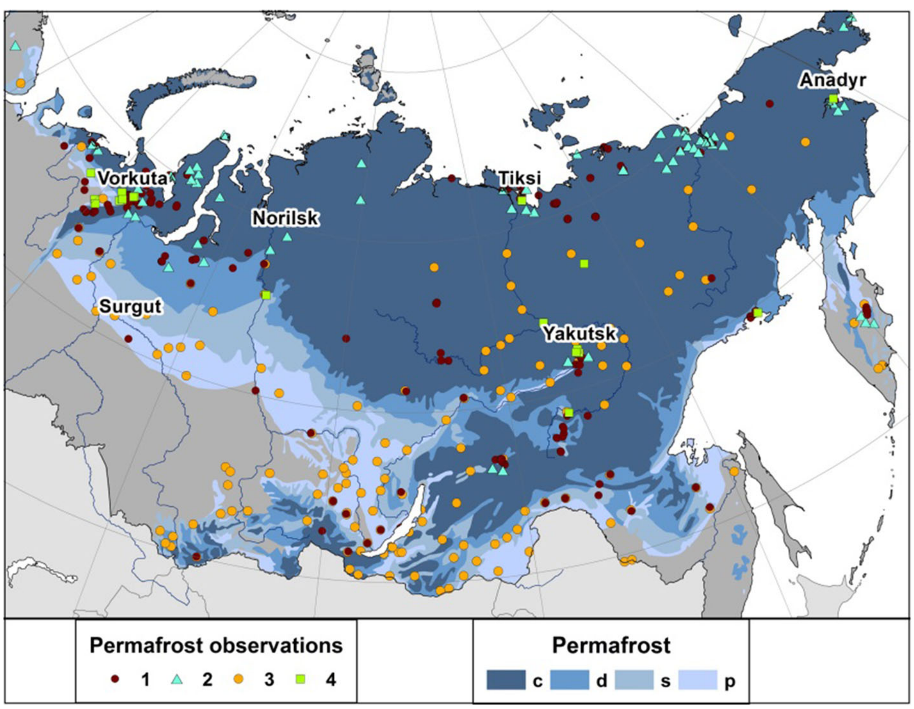

Fig. 1 Russian permafrost observations. 1–384 TSP boreholes with ground temperature observations at varying depths; 2–68 CALM sites with ALT observations; 3–146 weather stations with ground temperature observations up to 3.2 m depth; 4–35 permafrost monitoring plots; designation of permafrost zones, c continuous, d discontinuous, s sporadic, p isolated patches

each of the two factors, air temperature and snow depth, have had on the variations of the measured T_s at 3.2 m depth in different regions in the period 1980–2019.

Sparse and unevenly distributed ALT and T_s observations conducted over a relatively short time period cannot provide holistic understanding of the large-scale permafrost changes. Upscaling techniques are, therefore, needed to fill geographical and temporal gaps. In a manner similar to model-based integration of raw meteorological observations into gridded data products, we performed permafrost reanalysis to generalize the observations over space and time.

Permafrost reanalysis, detailed in (Anisimov et al. 2020), is a two-step procedure involving data assimilation and calibration of the permafrost model, followed by calculation of T_s and ALT in the grid nodes spanning the permafrost domain. Models of different complexity have been developed for calculating T_s and ALT through climatic (air temperature, snow depth) and environmental (topography, vegetation, soil) parameters. We used the dynamic permafrost model of the State Hydrological Institute, which is detailed in the Electronic Supplementary Material (ESM). In many coastal regions in West Siberia and almost everywhere on the Yamal Peninsula, soil contains brine in soil pore space, which is called cryopeg. Cryopegs stay unfrozen at negative temperatures as low as – 6 °C and in some cases even lower, depending on the salinity and soil texture. Under lower temperatures, the fraction of the liquid brine gradually decreases. The permafrost model was adjusted to explicitly account for such freezing temperature depression, and for the effect of brine diffusion on soil thawing.

We calibrated the permafrost model using the two-step approach which is detailed in (Anisimov et al. 2020). Firstly, we used CRU TS v4.03 gridded monthly air temperature and precipitation data for the period 1980–2019 as climatic forcing and performed ensemble model runs with disturbed parameters until we obtained the best least squares fit of available observations. We then used T_s records from 35 experimental plots at the Melnikov Permafrost Institute. We divided these records into three classes representing different climatic, vegetation, soil, and permafrost conditions, ranging from sites with low T_s and shallow ALT in the high Arctic to sites with near-zero T_s and deep seasonal thawing in the discontinuous and sporadic permafrost zones. We made classed fine tuning of the model and developed three standardized sets of the parameters, one for each class, which yielded the best fit of observations in the corresponding class. Model calibration and fine tuning is illustrated in Figs. S3 and S4 in the ESM.

We used gridded monthly-mean air temperature and precipitation data for the period 1980–2018 from the CRU TS v4.03 database as climatic forcing for the permafrost model. In the predictive calculations for the mid-21st century, we used an ensemble climate projection based on a subset of 14 CMIP5 Earth system models that demonstrate better-than-average agreement with observed temperature and precipitation trends in five Russian permafrost regions, as detailed in (Anisimov et al. 2017) and in the ESM.

We calibrated the permafrost model using T_s data from 384 TSP boreholes (AWI 2019), ALT data from 68 Russian CALM sites (Kokorev et al. 2018), continuous T_s records at 35 permafrost monitoring plots of the Melnikov Permafrost Institute (Anisimov et al. 2020), and daily air and soil temperature data from 146 Roshydromet weather stations (Fig. 1). We validated the model in a regional case study using a more than 40-year-long continuous record of permafrost, soil, snow, vegetation, and climatic parameters at the Kolyma coastal plain (East Siberia), conducted at the North-Eastern Research Station in Cherskiy.

Some observations and carbon models suggest that permafrost thawing under anaerobic conditions, such as in the wetlands, river valleys, lowlands, and thermokarst lakes, lead to increased surface–atmosphere methane fluxes (F_{ch4}) with potentially large impact on the global climate (Schuur et al. 2015). Besides the soil hydrology, this process depends on T_s and ALT. We calculated variations of these parameters in the historical period over the Siberian permafrost domain using permafrost reanalysis and compared the spatial patterns with satellite data on methane concentration in the lower atmosphere (C_{ch4}) for the period 2002–2019. We used C_{ch4} data obtained by the Infrared Atmospheric Sounding Interferometer (IASI) residing on the European Space Agency's MetOp polar orbiting satellites to retrieve information about F_{ch4} in representative locations with different topographic and biochemical conditions. In contrast, a conventional top-down approach requires an inverse model of the atmospheric transport. Instead of inverse modeling, we identified fingerprints of different permafrost sources on the variations of C_{ch4} in time and across space. In the annual cycle, we took into account the timing of methane emissions from different sources.

Several studies have demonstrated that the spatial pattern of C_{ch4} in the lower atmosphere is consistent with the pattern of F_{ch4} (Yurganov et al. 2016). At the macro-level, evidence comes from ground-level observations at NOAA stations (Dlugokencky et al. 2019a, b). They indicate lowering of C_{ch4} from Tiksi (delta of the Lena river) to Point Barrow (Alaska) and Alert (Canadian Arctic Archipelago), consistently, with the decrease of the soil carbon content, permafrost temperature, ALT, and F_{ch4} along this transect. Following (Yurganov et al. 2016), we used satellite data on C_{ch4}, detrended for latitudinal effects, as a proxy metric of the surface–atmosphere methane fluxes in

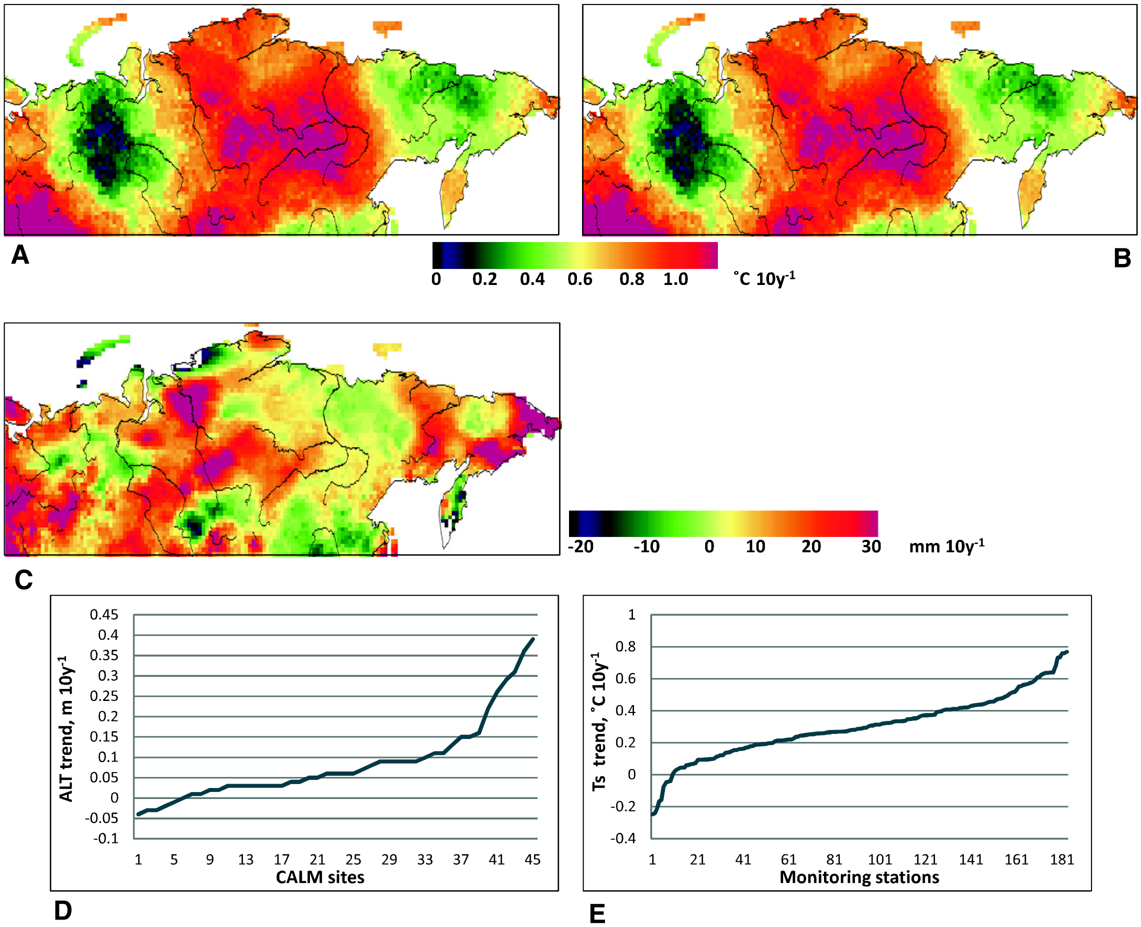

Fig. 2 Observed climatic and permafrost trends in the period 2002–2018. **a**, **b** summer (JJA) and annual mean air temperature, °C (10 year)$^{-1}$. **c** sum of precipitation in November–April, mm (10 year)$^{-1}$. **d** ranked ALT trends at 45 CALM sites with more than 10 years of observations, m (10 year)$^{-1}$. **e** ranked soil temperature trends at 146 stations in the period 1980–2019, °C year^{-1}

Siberia. We assumed that F_{ch4} at the monthly time scale is proportional to the local C_{ch4} deviation from the latitudinal-mean, i.e.,

$$F_{ch4} = k\, C_{ch4}, \quad (1)$$

where k is an empirical coefficient, estimated by substituting the modern F_{ch4} and C_{ch4} values into Eq. (1). Methodology of calculating k is detailed in (Yurganov et al. 2016).

We developed a statistical model of methane emission by evaluating the predictive value of several permafrost and climatic parameters and selecting the best predictors of F_{ch4}. We used the model forced with the CMIP5 ensemble climate projection for the mid-21st century to evaluate the increase of F_{ch4} from thawing permafrost and, following (Anisimov 2007), evaluated the effect on the global temperature.

Analysis of digital maps and satellite data was made using the IDRISI Selva v.17.00. geographic information system.

RESULTS

Air temperature and snow depth are the key climate factors governing permafrost changes. Maps in Fig. 2 illustrate the trends in these parameters in the recent period 2002–2018. Warming is more pronounced in West Siberia, where air temperature has been rising by 0.8–1.2 °C per decade in all seasons. In East Siberia, temperature changes were not uniform through the seasons. In summer, they were smaller than elsewhere in Siberia, while the mean annual air temperature (MAAT) was rising by 0.8–1.0 °C per decade. Winter precipitation changes were not uniform across space, ranging from a more than 20 mm per decade increase in the Yenisey and Kolyma river valleys to near-zero or small negative changes in the rest of Siberia (Fig. 2c).

Figure 2d, e illustrate ranked ALT and T_s trends calculated from the observational data. Both parameters exhibit variations across stations ranging from slight negative values at few locations to high positive values.

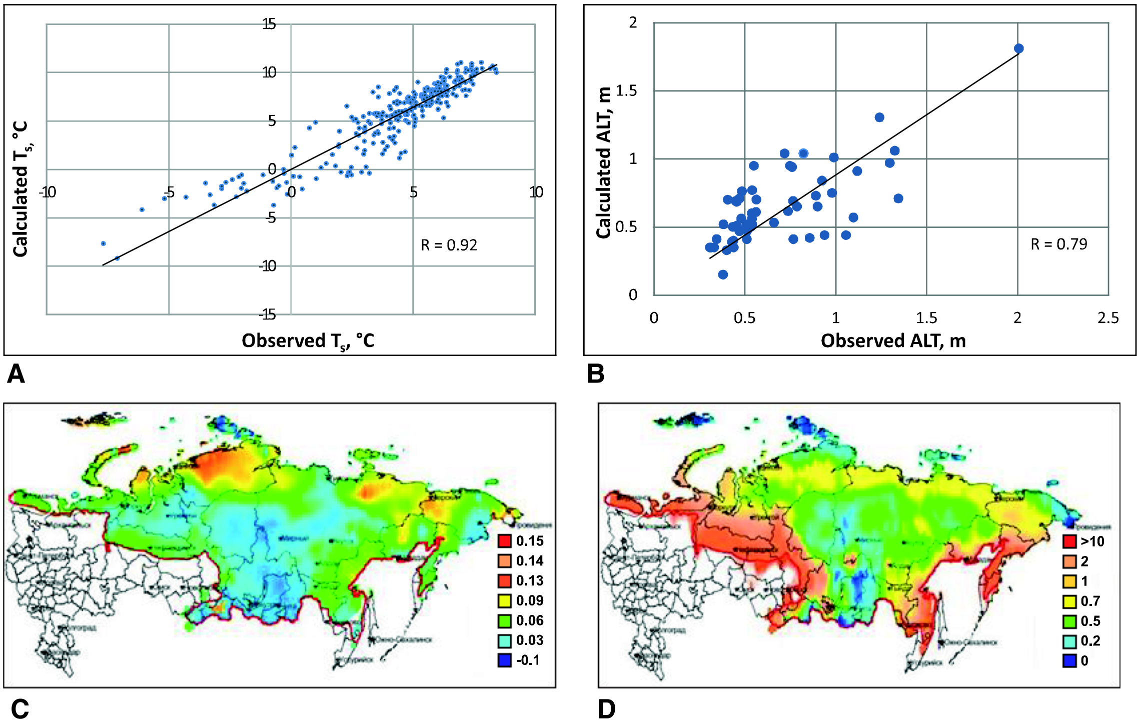

Fig. 3 Upper panels—scatter plots of observed *vs* calculated T_s (**a**) and ALT (**b**). Lower panels—calculated trends in T_s at 3.2 m depth, °C year^{-1} (**c**) and ALT, cm year^{-1} (**d**) during the period 1990–2018

Analysis of data from the weather stations over the longer period 1980–2019 indicated that the effects of air temperature and snow depth on T_s changes in the upper 3 m layer differ by region. In West Siberia, MAAT variation has a greater effect than snow depth. It explains up to 30% of T_s variation ($R^2 = 0.3$) at about half of the stations. At the other stations, neither of these factors alone account for more than 10% of variation, owing to the damping effect of the thick snowpack. In East Siberia, winter precipitation norms are small, and even a slight increase in the snow depth leads to a discernible T_s rise, as will be demonstrated further in the Cherskiy case study (presented below). In this region, snow depth explains up to 20% of the total T_s variation ($R^2 = 0.2$), which is about the same as the effect of the MAAT variation. In all other regions with higher winter precipitation normal, the snow depth accounts for less than 10% of the T_s variation.

We used the calibrated permafrost model for the reanalysis of T_s and ALT in the period 1990–2018. Scatter plots in the upper panels in Fig. 3a, b illustrate the correspondence between the reanalysis and observations. Reanalysis accurately fits the T_s observations at 3.2 m depth ($R = 0.92$). ALT exhibits significant variations even at small distances due to small-scale topographic, hydrological, vegetation, and edaphic factors. Such factors cannot be explicitly addressed in the deterministic permafrost model, which explains the larger spread of ALT (Fig. 3b) than T_s (Fig. 3a).

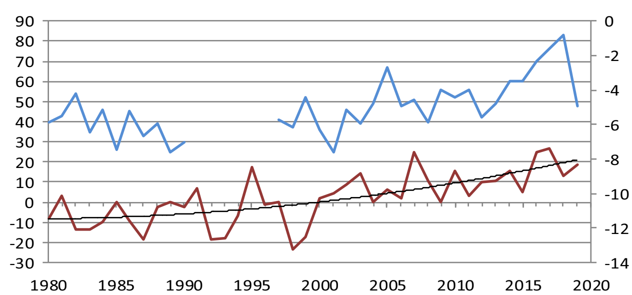

Fig. 4 Changes of the maximum snow depth (blue line) and MAAT (red line) in the Kolyma lowland in the 1980–2019 period. Unpublished data of Cherskiy research station

To minimize the effect of model biases and to highlight the components associated with climatic change, we calculated the T_s and ALT trends over the 1990–2018 period using the reanalysis data (Fig. 3c, d). Calculated trends are consistent with the observations. "Cold" permafrost on the West Siberian coastal plain and in the Kolyma lowland in Fig. 3c demonstrates the highest rates of warming because it does not involve the latent heat exchange associated with ground ice melt. Calculated (Fig. 3d) and observed ALT trends are in good agreement at both local and macro levels. The calculated trend, averaged over the Siberian domain, is 11 cm per decade, which is consistent with the average trend at 45 CALM sites of 8.7 cm per decade (Fig. 2d). This is not surprising given that the observations are biased towards coastal lowlands and do not capture the largest rates of ALT changes, which occur in the southern permafrost zones.

Cherskiy case study

Figure 4 illustrates snow depth and MAAT changes in the Kolyma lowland over the 1980–2019 period. According to the observations at the Cherskiy Research Station (Anisimov et al. 2020), significant increases in snow depth and MAAT in the past few years have led to warming and widespread abrupt thawing of permafrost in the coldest northernmost zone, in which mosses do not constitute a significant proportion of the ground cover. The Cherskiy case study illustrates the wider permafrost changes in many locations across East Siberia, where snow depth plays a more important role than air temperature and thereby has an important effect on carbon emission.

In the 1990s, the MAAT in Cherskiy was about – 11 °C, permafrost temperature was between − 6 and – 9 °C, and snow depth was 0.35–0.40 m. ALT varied in the range 0.35–1.60 m depending on the topographic and soil conditions, and soil froze completely during November to January. In the following two decades, MAAT and permafrost temperature increased by 3 °C. In the recent few years, snow depth nearly doubled, and the difference between the permafrost and air temperatures increased by 3–5 °C. The upper permafrost layer warmed to near-zero temperatures and began thawing in areas without an insulating cover of mosses. By 2017, ALT had increased up to 0.8 m in the wetlands and up to 2.2 m in the carbon-rich yedoma soils. In the following snowy winter, only the upper 0.4–1.0 m soil layer froze from the top. It then thawed by early June. Permafrost thaw continued, and in the fall propagated up to 3 m depth in dry soils, and up to 5 m depth in an area that was stripped of its moss cover and laid bare by fire 70 years ago. Similarly abrupt permafrost thaw has been observed in Srednekolymsk, 500 km to the south of Cherskiy. In the fall of 2018, the atmospheric monitoring station in Ambarchik detected a sharp rise in CO_2 concentration. This was consistent with observed permafrost changes and is most likely attributed to emission from the deep carbon-rich Pleistocene soil. It also indicated that deep permafrost thawing has affected large territories, i.e., at a regional scale.

The 2018/2019 winter was cold, and snow depth was lower than in the previous 3 years (Fig. 4). The thawed layer beneath the seasonally frozen upper soil (open talik) was expected to refreeze, but survived throughout the year. Permafrost thaw continued, and in the fall, the talik penetrated below the 4 m depth. This occurred as a result of heat release from the microbial oxidation of soil carbon. Observations and theoretical calculations suggest that, by itself, soil microbial heating in the carbon-rich subsurface environment can lead to sustained thawing if the initial thaw penetrates below 1 m depth (Khvorostyanov et al. 2008).

Carbon fluxes from thawing permafrost

Observations in Cherskiy raise concerns that even in the coldest permafrost zone, in the absence of a surficial cover of mosses, sustained deep thawing may occur due to the combined effects of climate change and microbial heating. In this case, thaw may develop abruptly rather than gradually. This may lead to rapid release of significant amounts of carbon and subsequent microbial decomposition at a rate of up to 3% year^{-1} in the first 2–3 years (Elberling et al. 2013; Schädel et al. 2014). Given that the upper 3 m of soil contains about 1024 Pg C (Tarnocai et al. 2009), hypothetically, up to 10 Pg C year^{-1} may be released if all Siberian permafrost is affected by abrupt thawing. This is roughly equal to all anthropogenic emissions.

The bulk of the soil carbon is released through microbial oxidation in the form of CO_2. The high rate of microbial consumption in the freshly thawed soil places a direct constraint on oxygen availability in the upper 0.5–1.0 m layer. Below these depths oxygen content is low, and freshly thawed soil is anaerobic even in dry yedoma, as in wetlands, ponds, and thermokarst lakes. Anaerobic conditions favor the production of methane, which is a greenhouse gas 25–34 times more potent than CO_2 on a 100-year time scale (Myhre et al. 2013).

In Siberia, thawing permafrost in coastal lowlands and polygonal landforms leads to ground depressions and ponding. Ponds expand, merge into each other, and evolve into thermokarst lakes, which currently occupy 10–30% of the Arctic plains (Schuur et al. 2015). These lakes are surrounded by carbon-rich Pleistocene soils. Up to 30% of carbon in the eroding soil along the lake margins is transformed to methane (Walter Anthony et al. 2014, 2018). Due to a continuous supply of the freshly thawed organic material, lake margins show the Arctic-highest natural methane emission rates, on the order of hundreds g m^{-2} year^{-1} (Walter et al. 2006). This is two to three orders of magnitude higher than in the centers of the lakes, where the labile carbon has mostly been decomposed. Against this background, there is a pressing need for studying large-scale methane emissions from thawing permafrost with differentiation into yedoma, wetlands, and thermokarst lakes. We addressed this task in the large scale using C_{ch4} satellite data.

Satellite records of C_{ch4} are relatively short (records date only from September 2002) and demonstrate significant interannual variations in the warm months. There are not enough data for robust evaluation of trends; we, therefore, studied changes of C_{ch4} departures from the latitudinal-mean between the 2011–2019 and 2002–2010 periods. The maps in Fig. 5 illustrate such changes in July (A) and in September (B). In July F_{ch4} from wetlands are at their annual maximum, while emissions from the thermokarst lakes and yedoma are maximized in September.

The map in Fig. 5a demonstrates up to 3 ppb higher than for the latitudinal-mean C_{ch4} increase in July over north-western Siberia. This is consistent with the abundance of swamps in this region (Fig. 5c) and with the pattern of the summer temperature changes in Fig. 2a. In the north, the summer warmth deficit places a direct constraint on methane emissions. In accord with the summer warming, emissions increased above the latitudinal-mean in north-western Siberia and decreased by 5–7 ppb in the European north and in eastern Siberia, where the summer temperature changes were less pronounced. In the south, the situation is different because of the drying trend since 1999, which reduces methane emissions from wetlands (Bousquet et al. 2006).

In September changes between the two periods have a reverse pattern, with a significant C_{ch4} rise by 5–8 ppb vs the latitudinal-mean in many regions of East Siberia and smaller increases in most other permafrost regions. This is consistent with the timing, geographical location, and biogeochemistry of different methane sources. The map in Fig. 5b demonstrates several hot spots, such as in the central Yakutian plain, the Bykovskoi Peninsula in the Lena River delta, Novosibirskiy and Ljahovskoi islands, the coastal lowland between the Yana and Indigirka rivers, and in the Kolyma lowland. Deep thawing of the carbon-rich yedoma, as described in the Cherskiy case study, accelerating coastal erosion and expansion of the wide-spread thermokarst lakes increase September methane emissions in these regions over the past decade. Observed C_{ch4} changes in September are consistent with the rise in MAAT (Fig. 2b), which led to increases in T_s and ALT. At the macro-scale, Fig. 5d illustrates the coherence ($R^2 = 0.57$) between the interannual variations of the calculated ALT and C_{ch4} averaged over the Siberian permafrost domain and the rising trends in both parameters.

We used a statistical model to evaluate the effect of changing Siberian wetlands on C_{ch4} under climate conditions projected for the future. Public perception often associates such changes with the "methane bomb" that may have potentially large impacts on the global climate and economy (Whiteman et al. 2013). The map in Fig. 6 demonstrates the June–July mean C_{ch4} changes between the mid-21st century and the baseline period 2003–2019. It was constructed using the multifactorial regression model with 3 predictors, June and July air temperatures, and the June–July precipitation sum at 1 by 1 lat/long grid nodes spanning the permafrost region.

A direct correspondence exists between the spatial pattern of the predicted C_{ch4} changes in Fig. 6 and the fraction of land occupied by wetlands in Fig. 5c. The great West Siberian swamps of the Vasuganskaia plain and the lowlands between the Lena and Vilyi and the Yana and

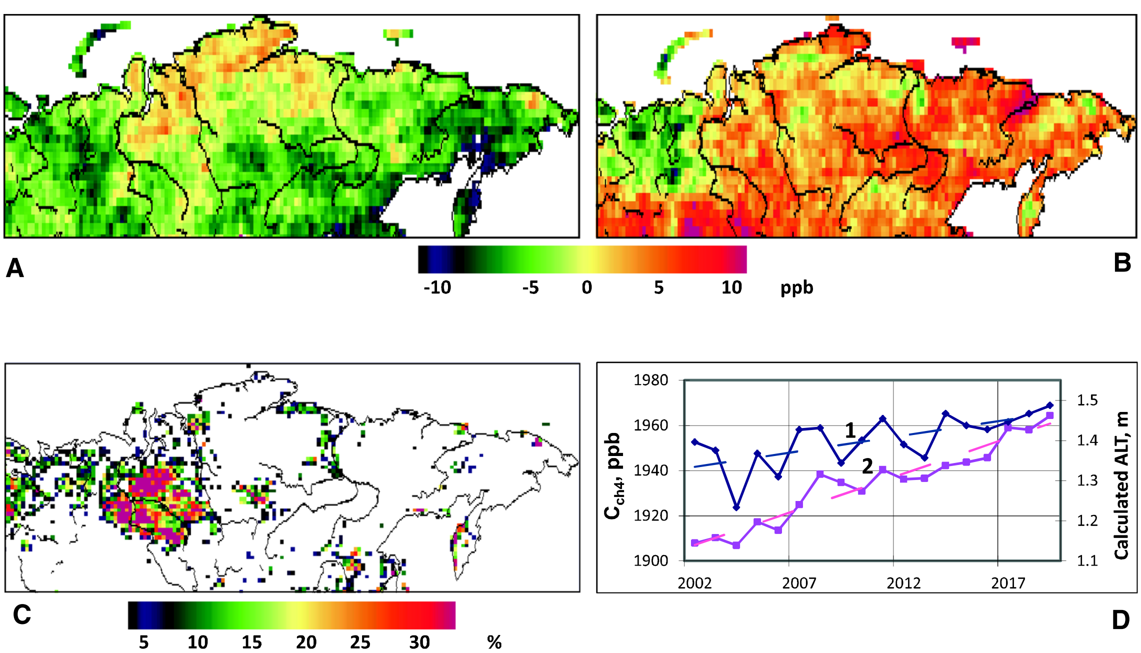

Fig. 5 Differences in CH_4 concentrations (ppb) averaged over the two periods, 2011–2019 and 2002–2010, for July (**a**) and September (**b**). **c**-fraction of land occupied by wetlands (%). **d**-interannual variations of the calculated ALT (m, purple lower line 2) and C_{ch4} in September (ppb, blue upper line 1), averaged over the Siberian permafrost domain

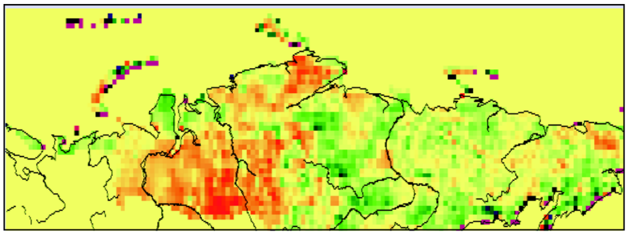

Fig. 6 Mean June–July C_{ch4} changes (ppb) projected for the mid-21st century, relative to the 2003–2019 reference period

Indigirka rivers demonstrate the largest projected positive changes of up to 15 ppb above the latitudinal-mean. The model predicted near-zero and slight negative changes over eastern Siberia, where different factors are likely to compensate or outweigh each other. The interplay of several competing factors is exemplified by the rises in air temperature, precipitation, and ALT, which enhance emissions, against the soil drying and lowering of the soil water levels, which have the opposite effect and ultimately lead to a shift from CH_4 to CO_2 emission.

Table 1 summarizes data on atmospheric methane concentrations and emissions from Siberian wetlands under the baseline climate conditions and those projected for the mid-21st century. Using GIS technology, we divided the digital map in Fig. 6 into domains with positive (D_1, reddish colors) and negative (D_2, greenish colors) projected C_{ch4} changes. We next calculated areas (S) of each domain and areal-mean C_{ch4} values for the baseline and mid-21st century periods. Contemporaneous methane emission from the Siberian wetlands is estimated at about 24–33 Tg year^{-1} (Anisimov 2007), of which 22–28 Tg year^{-1} fall into D_1 (West Siberian wetlands), and the remaining 2–5 Tg year^{-1} into D_2 (East Siberia and Chukotka). A recent review paper (Masyagina and Menyailo 2020) suggests that these numbers may be overestimates, but we keep them for the purpose of evaluating the maximum potential effect on the global temperature.

Table 1 Summary of changes in atmospheric methane concentrations and emissions from Siberian wetlands under the baseline and projected for the mid-21st century climate conditions

Domain	S, 10^6 км^2	2003–2019		Mid-21st century		
		C_{ch4}, ppb	F_{ch4}, Tg year^{-1}	C_{ch4}, ppb	F_{ch4}, Tg year^{-1}	k, Tg year^{-1} ppb^{-1}
D_1	1.514	5.73	22–28	9.70	37.2–47.4	3.84–4.89
D_2	1.351	2.68	2–5	− 3.09	0–0.36	0.75–1.87

We used Eq. (1) and the projected mid-21st century C_{ch4} changes to obtain information about future methane emission. According to our results, F_{ch4} from Siberian wetlands may increase by less than 20 Tg year^{-1}. Given that the residence time of CH_4 in the atmosphere is estimated at about 12 years, 20 Tg year^{-1} emission will increase the equilibrium atmospheric content by 240 Tg or by 88 ppb globally. Radiative forcing of methane is estimated at 3.63×10^{-4} w m^{-2} ppb^{-1}(Myhre et al. 2013) and 88 ppb will increase it by 3.19×10^{-2} w m^{-2}. Given that the climate sensitivity to radiative forcing is about 0.5°C w^{-1} m^{-2}, it will lead to less than 0.02 °C global temperature rise.

DISCUSSION AND CONCLUSIONS

Despite observational evidence, the role of climate in permafrost changes and consequent impacts is contested in Russia by many stakeholders, practitioners, decision-makers, and even conservative permafrost scientists (Anisimov and Orttung 2019), with some arguing that (1) permafrost is climate resilient, survived the warmer epochs in the past, and is unlikely to shrink dramatically in the near future; (2) under the conditions of modern global warming permafrost gets warmer, cooler, or stays unchanged depending on local conditions, which is exemplified, respectively, by 71, 12, and 40 out of 123 studied sites globally, according to (Biskaborn et al. 2019); (3) anthropogenic and technogenic factors, land use, and wild fires outweigh the effect of climate change, leading to massive and rapid landscape transformations in the permafrost environment.

Many of these arguments would not have arisen if there were accessible representative data on modern large-scale changes in the climatic regime, state of permafrost, and carbon emissions in Siberia, and nuanced theoretical studies that break down different types of factors governing such changes. The results of this study address this public need and draw a consistent pattern of the interrelated environmental changes in Siberia.

The findings of this study contribute to the scientific basis for discourse on environmental policymaking in Russia. Internationally, accents in recent years have been placed on developing environmental policies targeted at the implementation of the Paris Climate Agreement. At the country level, an important role is played by the so-called nationally determined contributions (NDCs), which are voluntary pledges to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. By definition, NDCs have to be "ambitious" and set "with the view to achieving the purpose of the Agreement". In practice, however, formulation and implementation of NDCs are complicated by the intrinsic conflict between the global goals and the national-level costs to achieve them (Höhne et al. 2017).

Concern has been expressed that the mechanisms of and the expectations from the Paris Agreement bear little or no connection to the socio-economical and biogeochemical realms (Spash 2016). Analysis presented in (Tørstad and Sælen 2018) indicates that such realms may have a significant impact on Russian environmental policymaking. Even the most accurately designed NDCs and environmental policies cannot advance if they are not supported by the public. A case in point is the public's perception of the hypothesized "methane bomb." Media treatment portrays an unavoidable and potentially catastrophic effect of thawing Siberian wetlands on climate. This raises a question about fairness for Russia in climate negotiations. NDCs cannot get widespread public support in Russia until their effect is compared with the effect of natural processes. Against the background of the unavoidable and potentially catastrophic effect of thawing Siberian wetlands portrayed in the media, even the most restrictive and societally expensive pledges to reduce anthropogenic emissions may seem ineffective to the public.

NCDs and the overall success of the Paris Agreement depend directly on the awareness of the national stakeholders, decision-makers, and general public about the costs and benefits of particular pledges and the feasibility of implementing them within a prescribed time frame. The results of our study advance the "benefit" component of the Russian NCD, demonstrating that the "methane bomb" concept is not supported by observations and modeling, and that the feedback between thawing Siberian wetlands and the global climate has been significantly overestimated. This finding is in line with the conclusion of the recent study (Christensen et al. 2019), which demonstrated that the mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase.

Our results raise another concern about the abrupt deep thawing of yedoma and release of Pleistocene carbon, with the potential consequences for the global climate. Analysis of the isotopic ^{14}C data presented in (Dyonisius et al. 2020) suggests that this is unlikely, because analogous warming during the last deglaciation did not trigger CH_4 emissions from the old carbon reservoirs. At the same time, the Cherskiy case study demonstrates that thawing could affect deep Pleistocene soil layers within a few years even at the coldest permafrost locations, indicating the need for further studies.

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