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Modelled present and future thaw lake area expansion/contraction trends throughout the continuous permafrost zone

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Abstract

Thaw lakes and drained lake basins are a dominant feature of Arctic lowlands. Thaw lakes are a source of the greenhouse gas methane (CH_4), which is produced under anaerobic conditions, while drained lake basins are carbon sinks due to sedimentation. Besides feedbacks on climate, the development of thaw lakes due to the melt-out of ground ice and subsequent ground subsidence, can have significant impacts on the regional morphology, hydrology, geophysics and biogehemistry.

Permafrost degradation as a result of climate warming, which is proceeding considerably faster in high latitude regions than the global average, could lead to either an increases in lake area due to lake expansion, or decrease due to lake drainage. However, which process will dominate is elusive. Therefore understanding thaw lake dynamics and quantifying the feedbacks related to thaw lake expansion and contraction are urgent questions to solve.

We apply a stochastic model, THAWLAKE, on four representative Arctic sites, to reproduce recent lake dynamics (1963–2012) and predict for the future changes under various anticipated climate scenarios. The model simulations of current thaw lake cycles and expansion rates are comparable with data. Future lake expansions are limited by lake drainage. We suggest further improvements in the area of enhancing the hydrology component, and operation on larger scales to gauge the impacts on lacustrine morphology and greenhouse gas emissions.

1 Introduction

Thaw lakes and drained lake basins are dominant features of northern high latitudes, in particular lowlands along the coast and continental interior of Siberia and Alaska (Arp and Jones, 2008; Grosse et al., 2013). Unconsolidated sediments in these areas are permanently frozen and usually supersaturated with ice, with ice volumes up to 90 % (Mackay et al., 1992; Kokelj and Jorgenson, 2013). The development and evolution of thaw lakes due to the melt-out of ground ice and subsequent ground subsidence, could quickly alter regional morphology (Hussey and Michelson, 1966; Hinkel et al., 2005; Chen et al., 2013), hydrology (Pohl et al., 2009; Bense et al., 2012; Walvoord et al., 2012), heat balance (Hinkel et al., 2012; Matell et al., 2013), and above all, the permafrost carbon budget for instance by releasing methane (CH_4) to the atmosphere (Phelps et al., 1998; Walter et al., 2006; Walter Anthony and Anthony, 2013; Takakai et al., 2008). CH_4 has a significantly positive feedback on global warming (IPCC, 2013).

It has been hypothesized that thaw lakes show a cyclic behaviour, going through repetitive stages of lake initiation, growth and drainage (Katamura et al., 2006; Morgenstern et al., 2013; Lenz et al., 2013). Lakes begin to form following the disturbance of the thermal equilibrium of the ground, such as pooled water, disruption of vegetation cover, anthropogenic disturbance, and importantly, climate change, particularly changes in air temperature and precipitation. Lakes expand by conducting heat from lake water to the surrounding and underlying permafrost, resulting in the erosion of their margins and subsidence of icy permafrost. This is further enhanced by wave erosion. As lakes grow, they often coalesce or connect with surface or subsurface drainage system and eventually become drained lake basins. As long as the climate permits, permafrost will return and the growth of thaw lakes may start again. The repeated cycles shape out a unique landscape scarred with overlapping thaw lake basins of various age and vegetation succession (Jorgenson et al., 2001; Brouchkov et al., 2004; Katamura et al., 2009; van Huissteden et al., 2011). However it has also been argued that this thaw lake cycle may not be fully developed in the present Holocene interglacial climate (Jorgenson and Shur, 2007).

Northern high latitudes are predicted to experience the greatest warming in the near future, ~5 °C by the end of the 21st century (IPCC, 2013). Permafrost degradation is expected for most Arctic regions, leading to either an expansion of total lake area due to formation of new ponds or thermal erosion along already existing lake shorelines (Osterkamp et al., 2000; Smith et al., 2005; Walter et al., 2006), or lake drainage, as ground thaw may create vertical or lateral conduits thereby changing regional hydrology (Yoshikawa and Hinzman, 2003; Smith et al., 2005; Riordan et al., 2006; van Huissteden et al., 2011). However, which process will dominate is largely unknown.

The lakes will in turn feedback on the climate system. Lake expansion will accelerate the anaerobic decomposition of old organic carbon, therefore increase the release rate of CH_4 to the atmosphere. Furthermore, recent study revealed that the lakes can be a substantial source of carbon dioxide (CO_2) Bastviken et al. (2011). Alternatively, the drained lake basins can act as carbon sinks as the uptake of CO_2 from the atmosphere by the vegetation (Hinkel et al., 2003; van der Molen et al., 2007; Kutzbach et al., 2007). Therefore quantifying changes in thaw lakes is of importance for understanding potential feedbacks to climate variability.

In this study, we apply a stochastic thaw lake dynamic model, THAWLAKE (van Huissteden et al., 2011), on four selected Arctic sites, to quantify the evolution of thaw lake coverage along a climatic gradient during the last fifty years, and predict the future changing trends over the coming decades under various anticipated climate scenarios.

2 Methods

2.1 Model description

THAWLAKE is a stochastic, landscape-scale two-dimensional model of thaw lake initiation, expansion and drainage. Compared with processed-based models, this has the advantage of computational efficiency and simplified parameterization, while essential processes of the thaw lake behaviour can still be simulated on a sufficiently large landscape scale. The latter feature is highly important in data sparse regions such as the Arctic area. A full description is given by van Huissteden et al. (2011).

The model is driven by climatic variables: mean annual precipitation (P), July air temperature (T_{jul}), and mean annual air temperature (T_{ann}).The model assumes linear relations between lake expansion and climatic variables and ice content. The rates of lake formation and expansion depend on the volumetric ice content of the subsoil and the deviations of P and T_{jul} from a dry and cold Pleistocene glacial reference climate, at which ice-rich permafrost is considered to be geomorphologically stable. Stochastic processes in the model are inroduced in the selection of ice-rich grid cells where new lakes are created, and the incidence of lake drainage, which is based on the distance of lake shore to the drainage system and precipitation. The lake drainage rate is related to P, and re-growth of ground ice depends on T_{ann}. The model runs yearly over an area of 400 km^2 subdivided into 500 × 500 grid cells, or 40 m × 40 m in size. Results are given by calculating the average and standard deviations of 100 model runs.

2.2 Simulations set-up

We select four sites from northern high latitudes underlain by ice-rich continuous permafrost to apply the model (Fig. 1). All areas are characterised by thermokarst features, covered with thaw lakes or drained thaw lake basins. The initial lake coverage and river networks are digitized from Google Earth Landsat images, taken on the date of 4 October 2013. This is different from the simulations in the previous study by van Huissteden et al. (2011), in which the model was configured with a fictious lake and fluvial system.

At all sites, the climate is subarctic according to the Köppen climate classification, their climatic properties are listed in Table 1. Site A (70°41′–70°52′ N, 156°54′–157°27′ W) is located on the Arctic Coastal Plain, northern Alaska in the United States. Volumetric ice content in this area averages 0.5 to 0.75 in the upper 2 m, and ice wedges may contribute an additional 0.1 to 0.2 (Sellmann et al., 1975; Eisner et al., 2005; Hinkel et al., 2003). Site B (69°15′–69°26′ N, 69°27′–69°57′ E) is situated on the western shore of the Yamal Peninsula, Kara Sea. The volumetric ice content of this location ranges between 0.3 to 0.5 (Streletskaya and Leibman, 2003). Site C (62°47′–62°58′ N, 130°45′–131°09′ E) is located on the eastern side of the lower Lena River in the Sakha Republic (Yakutia) of northern Siberia, Russia. Ground ice content in this site varies from 0.3 to 0.75 (Vasil'chuk et al., 2012; Biskaborn et al., 2013). Site D (70°41′–70°52′ N, 147°18′–147°51′ E) is centered on the Kytalyk tundra research station in North-eastern Siberia with the volumetric permafrost ice content of up to 0.8 (van Huissteden et al., 2011).

For the past 50 years, climatic drivers are calculated from daily observations of precipitation and air temperature, obtained from National climatic data center (http://www.ncdc.noaa.gov/), US National Oceanic and Atmospheric Administration (NOAA).

Future lake expansion as a result of Arctic warming is quantified by using simulated data from climate models from the 5th phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2011). We choose the output from four climate models under 2 emission scenarios, 2.6 (lowest) and 8.5 (highest), used in the Intergovernmental Panel on Climate Change (IPCC) Special Report (Vuuren et al., 2011). We have selected output of full Earth System models that include ocean and biogeochemical cycle components: MPI ESM (Giorgetta et al., 2013), BCC CSM1 (Wu et al., 2013), MIROC ESM (Watanabe et al., 2011) and HadGEM2 ESM (Collins et al., 2011) model output (available at http://cmip-pcmdi.llnl.gov/cmip5/). We extracted relevant climate data time series from the output of the models for land grid cells closest to the centre of our modelling areas.

3 Results

3.1 Current climate

The results from climatic trends analysis of the meteorological data (1963–2012) are shown in Table 2). The linear regression and F test indicates slight increases in mean July air temperatures (T_{jul}) and mean annual air temperatures (T_{ann}) at all four study sites with very strong significance for most time series, whereas no significant trends are found in total annual precipitation (P). This is in accordance with the latest IPCC assessment (IPCC, 2013).

The model simulates a reasonable thawlake growth-drainage cycle for all four study sites under current climate conditions (Fig. 2). Lakes expand over the past 50 years in responding to the rising air temperatures. The average lake area expansion rates are 0.15 %, 0.21 %, 0.09 % and 0.22 % per year for Alaska, Kytalyk, Marre-Sale and Yakutia, respectively, or 0.013, 0.017, 0.006 and 0.013 $\mathrm{km}^2\ \mathrm{km}^{-2}\ \mathrm{year}^{-1}$. Shrinkage occurs in some years by lake drainage. The Alaska site and Yakutia site show smaller drainage rates than the other two sites due to lower local drainage density (Fig. 1).

The results for all four study regions are similar to those of van Huissteden et al. (2011) configured with a fictitious lake and fluvial system. All sites show climate warming reflected by an increase of mean annual air temperature. Increases in modelled lake area are in a similar range as observation data in the continuous permafrost zone, although the available data are sparse and vary widely. Actual in-situ data are lacking, only at Kytalyk a single observation is available. In most cases, the studies are based on low-resolution image material and therefore inaccurate.

Image analysis of aerial photography by Jorgenson et al. (2006) revealed that the area of thermokarst pits in northern Alaska increased about 4 % over the period of 1982–2001, or approximately 0.2 % per year, whereas by comparing satellite imagery, Riordan et al. (2006) found that the Arctic Coastal Plain region had negligible change in the area of closed ponds since 1950s. Hinkel et al. (2007) concluded that in the continuous permafrost zone in Alaska, the landscape was stable and the drainage of lakes was limited for the latter half of the 20th century (1970s onwards). Smith et al. (2005) reported an increase of 12 % lake area in Siberian continuous permafrost region over ∼ 25 years (1973 to 1997–1998), or 0.48 % per year, by analyzing information retrieved from remote sensing images, whilst Walter et al. (2006) measured a 14.7 % increase in lake area in North Siberia over the period of 1974–2000, or 0.57 % per year. A study in the Northern Canadian Arctic (Labrecque et al., 2009) showed a reduction in lake surface area over 1951–2001. The opposing obseravations could be resulted from the interactions of climate change and catastrophic lake drainage; the latter one is paticularly important in this area (Marsh et al., 2009).

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3.2 Future climate

The future experiments are carried out at all four study sites, initialized with current lakes area coverage and ground properties. In all sites, the simulations show similar oscillation patterns of lake growth and decline. However, lake expansion dominates the first decades, in contrast, shrinkage outpaces expansion later on. The lake fractions increases at the beginning are primarily a consequence of elevated air temperature and precipitation, while the following decreases are a result of improved lake drainage (Figs. 3 to 6). The maximum thawed area fractions range from ∼ 0.17 (Marre-Sale) to ∼ 0.32 (Alaska), and thereafter reduced to much lower percentages by the end of this century.

The scenarios SRES 2.6 and SRES 8.5 produce different projections. Unexpectedly, the lower emission scenario, SRES 2.6, leads to higher thawed areas in sites Alaska, Kytalyk and Yakutia for most models. This was also observed by van Huissteden et al. (2011). During lake expansion period, the differences among models are marginal, while the drainage rates differ considerably thereafter. Compared with other models, MIROC predicts much higher air temperatures. As early as in the second half of the century, the mean annual air temperature modelled by MIROC already rises above 0° for the warmer sites, resulting in a complete permafrost thaw, which is beyond the performance limits of THAWLAKE, therefore the results deviate significantly from the other models.

4 Discussion

The THAWLAKE model is a highly simplified representation of the complex process of thaw lake expansion and contraction, which consists of interacting processes of permafrost thaw and geomorphological processes of lake bank erosion, sediment redistribution. Nevertheless, the model can model thaw lake dynamics on a landscape scale, which is difficult for models with more process details (van Huissteden et al.,

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2011). Here we have explored the performance of the model by modelling the behavior of thaw lake areas with a realistic lake and fluvial system configuration in various parts of the continuous permafrost belt in the Eurasian continent and Alaska.

For the most recent 50 years, climate warming leads to an increase of lake area ranging between 0.09 % and 0.22 %. The results are similar to those of modelled by van Huissteden et al. (2011), and the analysis based on remotely sensed images. The drainage rate simulated by THAWLAKE is conservative, as only drainage resulting from lake expansion encroaching on the drainage system is included (van Huissteden et al., 2011). However, as warming induces permafrost degradation and the thickening of active layer depth, the underground drainage is becoming more significant.

Projections for the future climate based on CMIP5 model simulations also show a similar pattern of lake change as modelled by van Huissteden et al. (2011). An initial increase in lake area is simulated, followed by rapid decrease of lake area as lake expansion causes lakes to make contact with the fluvial drainage system. All sites show a turning point between 2040–2080, depending on the climate input. Observations on lake area change which suggest that such a decrease could be realistic are those of Jones et al. (2012) on the Seward Peninsula in Alaska, where a net decrease of lake area has occurred by drainage of large lakes, and remote sensing data published by Smith et al. (2010), which show a decrease of lake area in the south of the permafrost zone.

In some cases, the CMIP5 model predicts warming climates that are beyond the limits of the THAWLAKE model was designed and tested. The model assumes a climate, in which permafrost can be re-established after lake drainage. The MIROC model simulates a generally warmer future climate than the other models, and causes mean annual air temperature to rise above 0° in the second half of this century for all areas with the SRES 8.5 emission scenario. For the westernmost Marre-Sale area, this also occurs with the other climate models under the SRES 8.5 scenario. In those cases, the model results in a rapid increase in lake area, which is likely not realistic. A rise of the temperature above 0° would also increase subsurface drainage on a much larger scale.

Slower warming (SRES 2.5 scenario models) results in a later onset of large scale lake drainage in the model, an effect that was also noticed by van Huissteden et al. (2011). This shows most strongly for the Kytalyk area (Fig. 4). The result leads to the paradoxical situation that mitigation of global warming would cause a longer persistence of thaw lake expansion and associated high CH_4 emission. Whether this effect is realistic or an artifact of the model is still to be decided. The model includes only lake drainage by surface contact of lakes with the drainage system, not by subsurface drainage. It can be argued that subsurface drainage could result in an earlier and less abrupt transition from lake area expansion to net lake area reduction, depending on the subsurface geology (Jorgenson and Shur, 2007; Marsh and Neumann, 2001). This might also result in a less strong dependency on the rate of climate warming. On the other hand, the mechanism is plausible: if lake expansion depends on the rate of warming, as it does in our model, also the probability of lake drainage by expansion into the fluvial drainage system increases.

Reduction in lake area is a negative feedback to the climate system. This could result in lower CH_4 emissions from the Arctic permafrost, as the drained lake basins are smaller sources of CH_4 than lakes and sinks for CO_2 van Huissteden et al. (2011). Moreover, regrowth of vegetation in the drained area can accumulate more soil carbon. Taking discontinuous permafrost into account, which is predicted to change the most dramatically and the lake area decline has already been observed in several regions Smith et al. (2010), we expect an enhancement in the negative climate feedback.

We did not translate the lake dynamics into CH_4 fluxes. van Huissteden et al. (2011) applied a simple emission factor approach, based on data of Walter et al. (2006) on lake fluxes and data by van der Molen et al. (2007) on the greenhouse gas balance of a mature drained thaw lake basin at the Kytalyk site. However, in this multi-region study, there are no GHG emission measurements that would support a better estimate than of calulated by van Huissteden et al. (2011). In the same vein, application of modelled

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emissions (e.g. Kessler et al., 2012) would require data on permafrost carbon content that is not available for our study regions.

THAWLAKE offers a functional framework to which mechanistic precision/process representation can be added. In particular lake drainage mechanisms, which are simplified in the current model, such as subsurface drainage, partial drainage and infilling by sediment should be included. The model operates on spatially appropriate scales ($> 100\,\mathrm{km}^2$) to further investigate the interaction of permafrost geophysics, geomorphological processes, climate and biogeochemistry. However, a consistent database of lake growth/drainage is essential for model parameterization and testing.

5 Conclusions

We applied the stochastic model THAWLAKE on four Arctic sites, to quantify the evolution of thaw lake area during the last 50 years, and predict the changes over the coming decades under various anticipated climate scenarios. Under current climate conditions, the model captures realistic thawlake growth-drainage cycles; the lake expansion and contraction rates are comparable with data. Future changes in air temperature and precipitation lead to a significant decline in lake coverage due to lake drainage. This has the potential to negatively feedback on the climate system. New features, such as including the probability of subsurface drainage, partial drainage of lakes, and including a scenario for complete permafrost thaw, are necessary in the future model development along with a consistent database to constrain model parameterization.

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Table 1. Climatic properties of four study sites, 1963–2012.

	T_{jul} (°C)	T_{ann} (°C)	P (mm year^{-1})
Alaska	4.55	−11.78	115.83
Kytalyk	10.83	−13.48	219.20
Marre-Sale	7.84	−7.83	303.05
Yakutia	18.84	−10.96	234.84

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Table 2. Climatic trends (Slope from linear regression) and their statistical significance (*P* value for probability), 1963–2012.

	P		T_{ann}		T_{jul}	
	Slope	P value	Slope	P value	Slope	P value
A: Alaska	0.38	0.32	0.07	0.00	0.05	0.00
B: Kytalyk	0.28	0.66	0.06	0.00	0.04	0.12
C: Marre-Sale	0.00	1.00	0.07	0.00	0.04	0.00
D: Yakutia	–0.73	0.23	0.05	0.00	0.04	0.05

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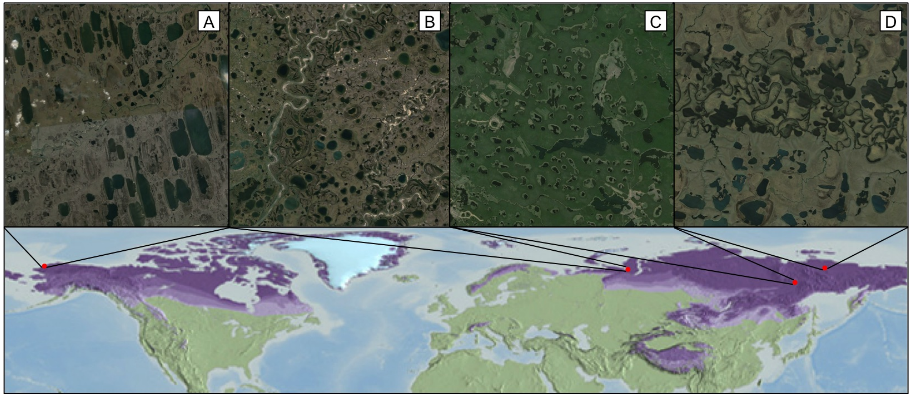

Figure 1. Study sites. **(A)** Alaskan Arctic Coastal Plain (70°41′–70°52′ N, 156°54′–157°27′ W), **(B)** Marre-Sale on Yamal Peninsula (69°15′–69°26′ N, 69°27′–69°57′ E), **(C)** Yakutia, Northern Siberia (62°47′–62°58′ N, 130°45′–131°09′ E) and **(D)** Kytalyk, North-eastern Siberia (70°41′–70°52′ N, 147°18′–147°51′ E).

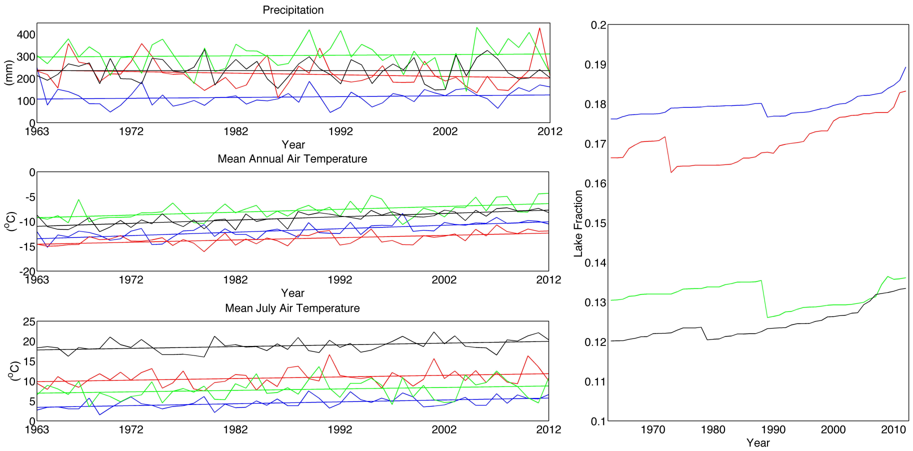

Figure 2. Thaw lake evolution under current climate condition. Blue: Alaska; Red: Kytalyk; Green: Marre-Sale; Black: Yakutia.

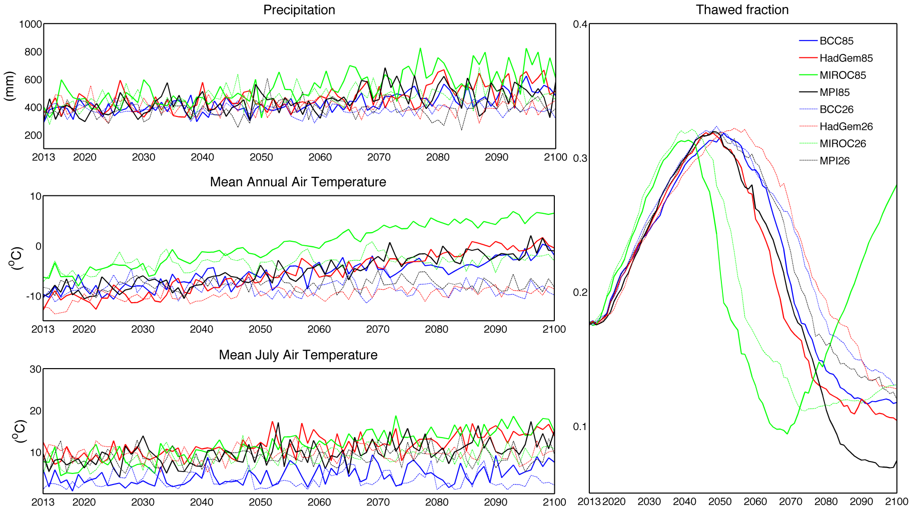

Figure 3. Projected future thawed area driven by outputs from four climate models under two emission scenarios, site Alaska.

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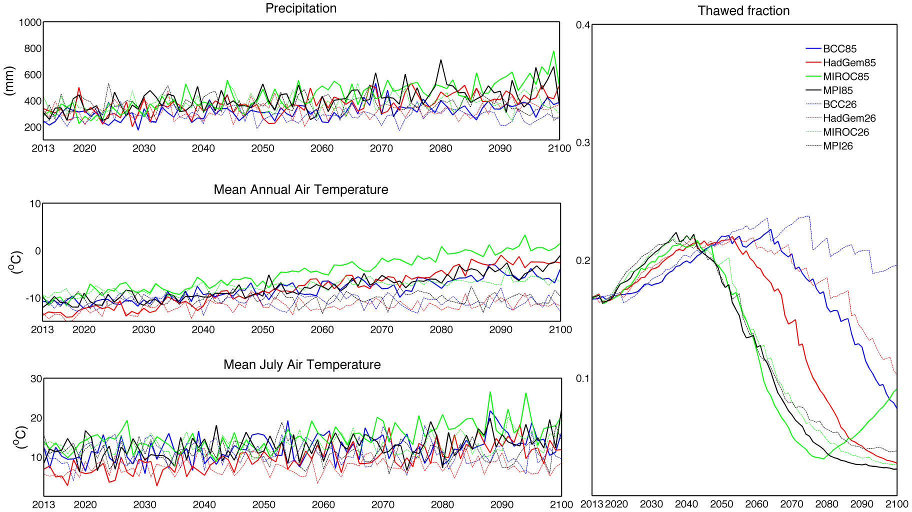

Figure 4. Projected future thawed area driven by outputs from four climate models under two emission scenarios, site Kytalyk.

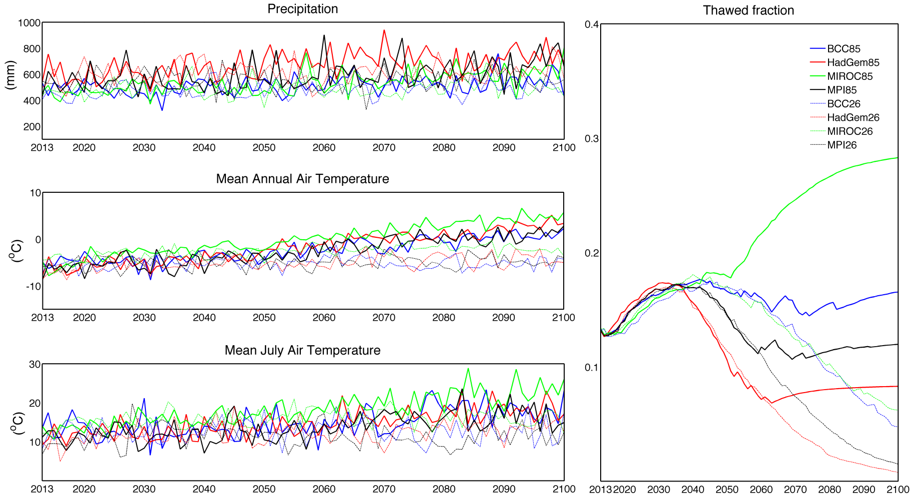

Figure 5. Projected future thawed area driven by outputs from four climate models under two emission scenarios, site Marre-Sale.

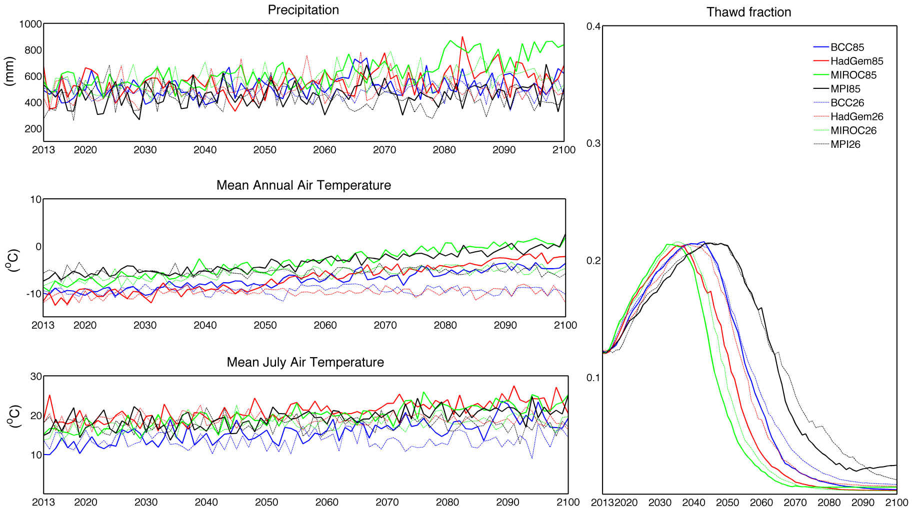

Figure 6. Projected future thawed area driven by outputs from four climate models under two emission scenarios, site Yakutia.