

Legacy effects of climate overshoot scenarios in permafrost-affected regions

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How long until terrestrial Arctic adjusts to steady atmospheric conditions?

Does steady-state of high-latitude ecosystems depend on preceding climate trajectory?

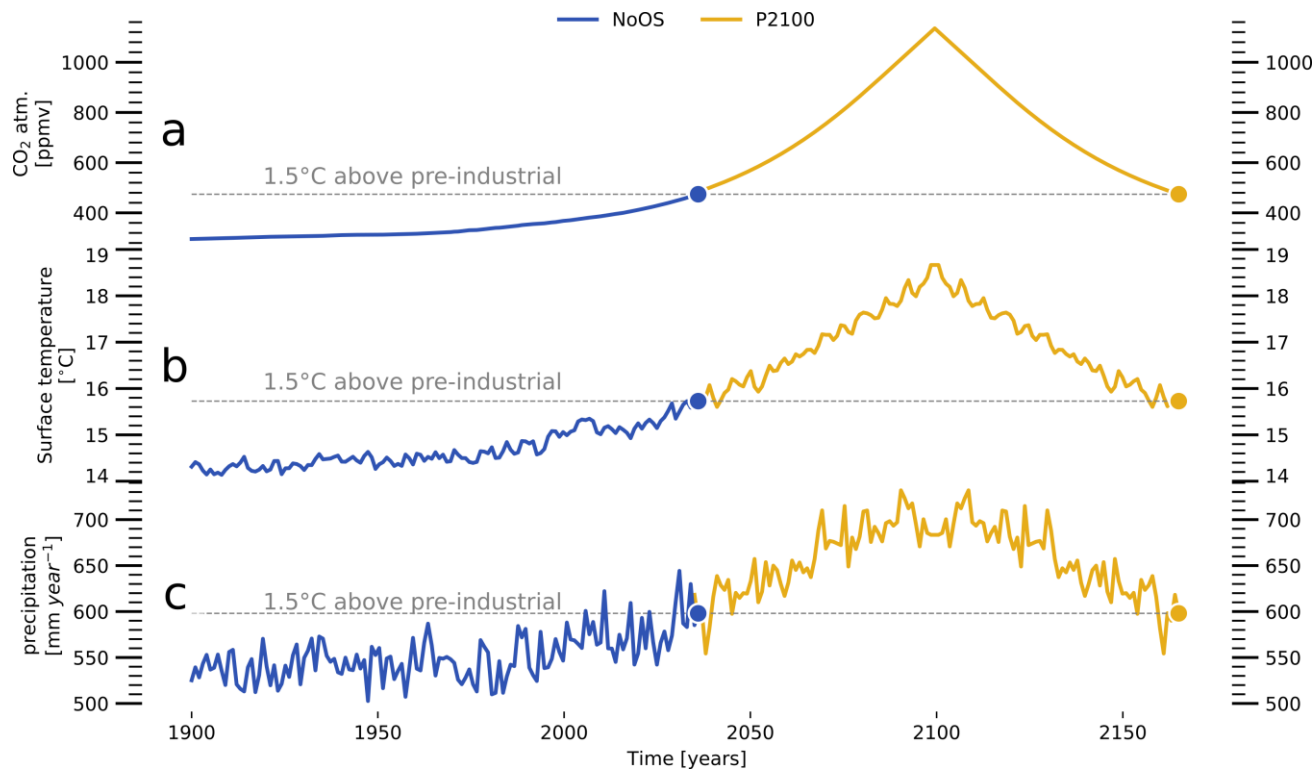
- *Experimental setup*
 - *Model & General setup (slide 5)*
 - *Forcing (slides 6 – 7)*
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Experimental Setup

- *Model*
 - Adapted version of JSBACH (de Vrese et al., 2021), the land surface model of the MPI-ESM (Mauritsen et al., 2019).
 - Offline-setup in which model is forced with prescribed atmospheric conditions
- *General setup*
 - Study targets the dynamics in northern permafrost regions (see fig. 1, right), under nontransient atmospheric conditions
 - Comparison of two scenarios in which climate stabilization is realized with (P2100) and without (NoOs) previously overshooting the climate target

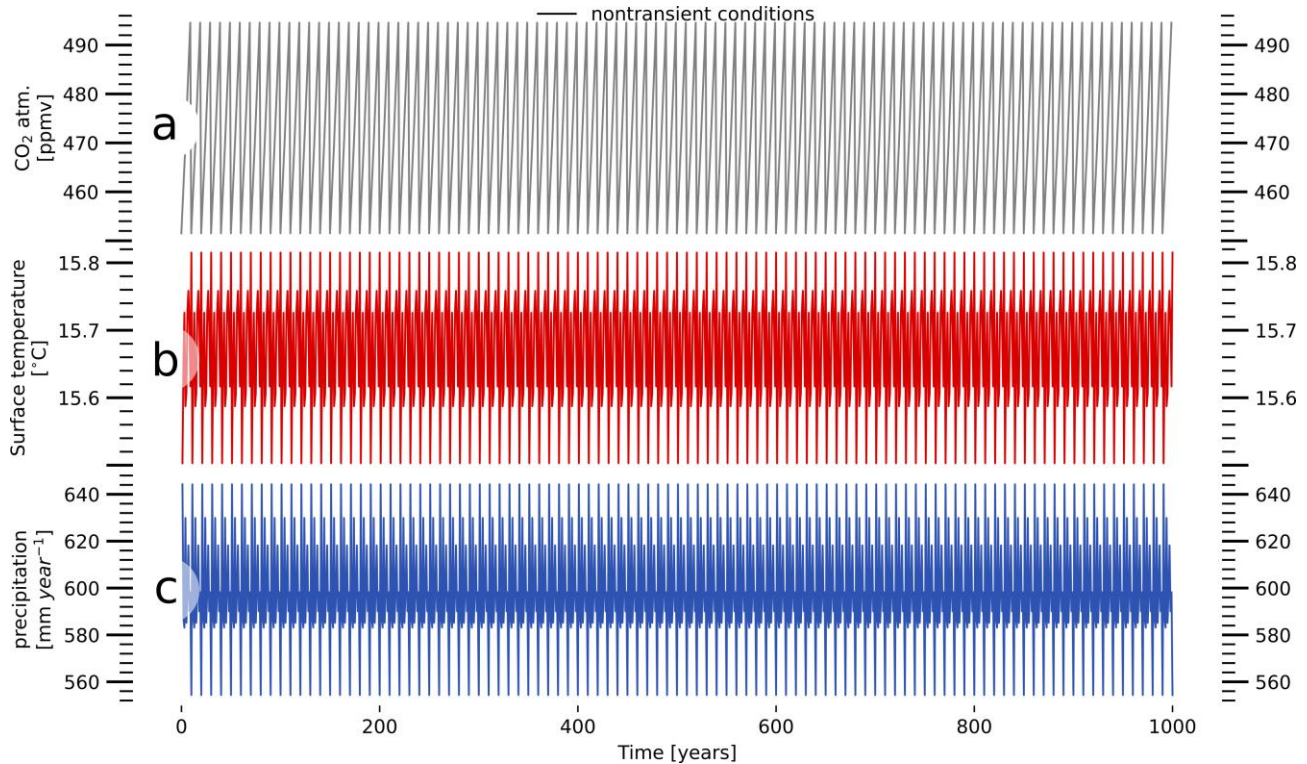


Fig.2: Conditions that were used to force the land surface model to the point of climate stabilization at 1.5°C above pre-industrial levels. a) Atmospheric CO2 concentration, b) (global) mean surface temperature, and c) precipitation rates. Note that the model is not forced by surface temperatures directly, but by atmospheric temperatures at a height of roughly 30 m and the surface incoming long- and short-wave radiative fluxes.



JSBACH is forced with output from simulations with the standard version of the MPI-ESM that were performed in the context of the 6th phase of the Coupled Model Intercomparison Project. These simulations cover the historical period – 1850 to 2014 – and a scenario period ranging between the years 2015 and 2100 (based on SSP5-8.5). There are no scenario simulations for a decrease in GHG concentrations and, for the overshoot-scenario (P2100), it is simply assumed that the decrease reverses the trajectory of the increase prior to the peak.

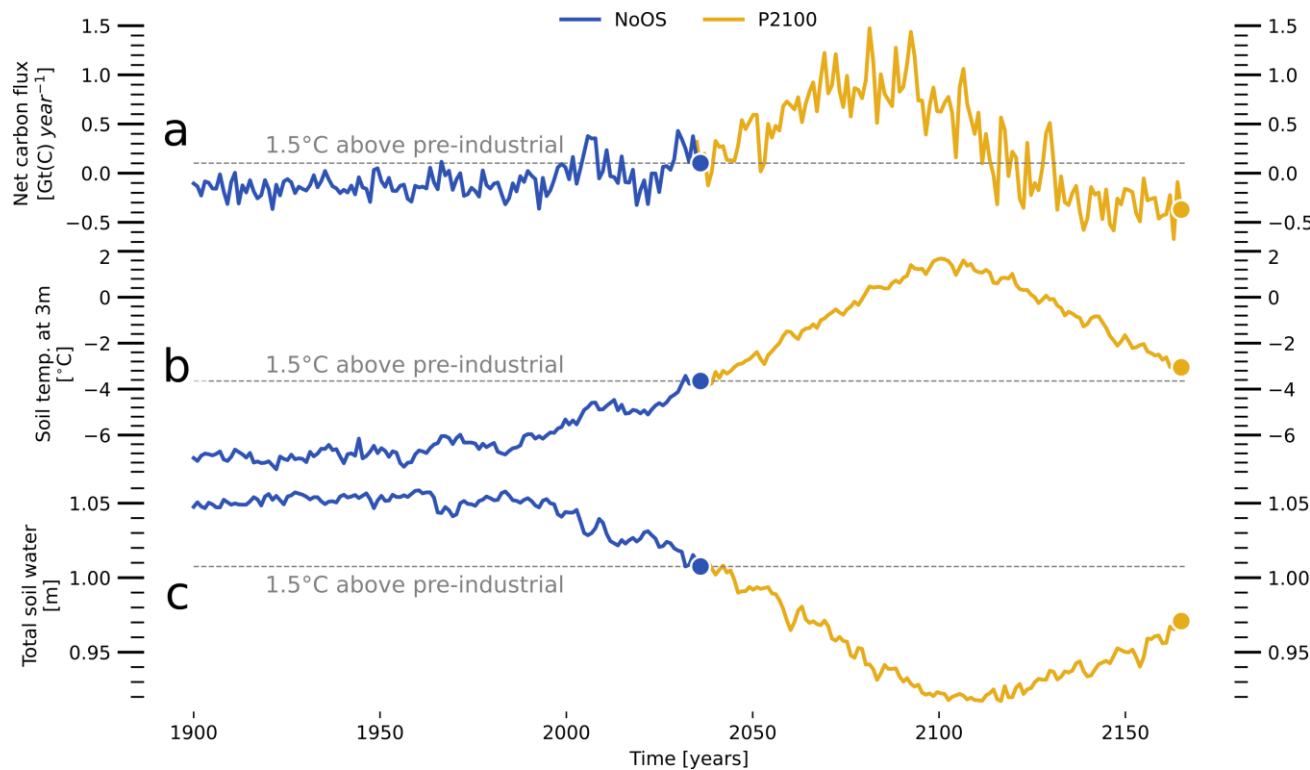
Fig.3: Nontransient forcing representative of the conditions at 1.5°C above pre-industrial levels. a) Atmospheric CO2 concentration, b) (global) mean surface temperature and c) mean precipitation rates. Note that the model is not forced by surface temperatures directly, but by atmospheric temperatures at a height of roughly 30 m and the surface incoming long- and short-wave radiative fluxes.



In simulations with the MPI-ESM, SSP5-8.5 reaches 1.5°C above pre-industrial levels around the year 2035. For simulations that target steady atmospheric conditions, we use the atmospheric forcing from the period 2030 - 2040.

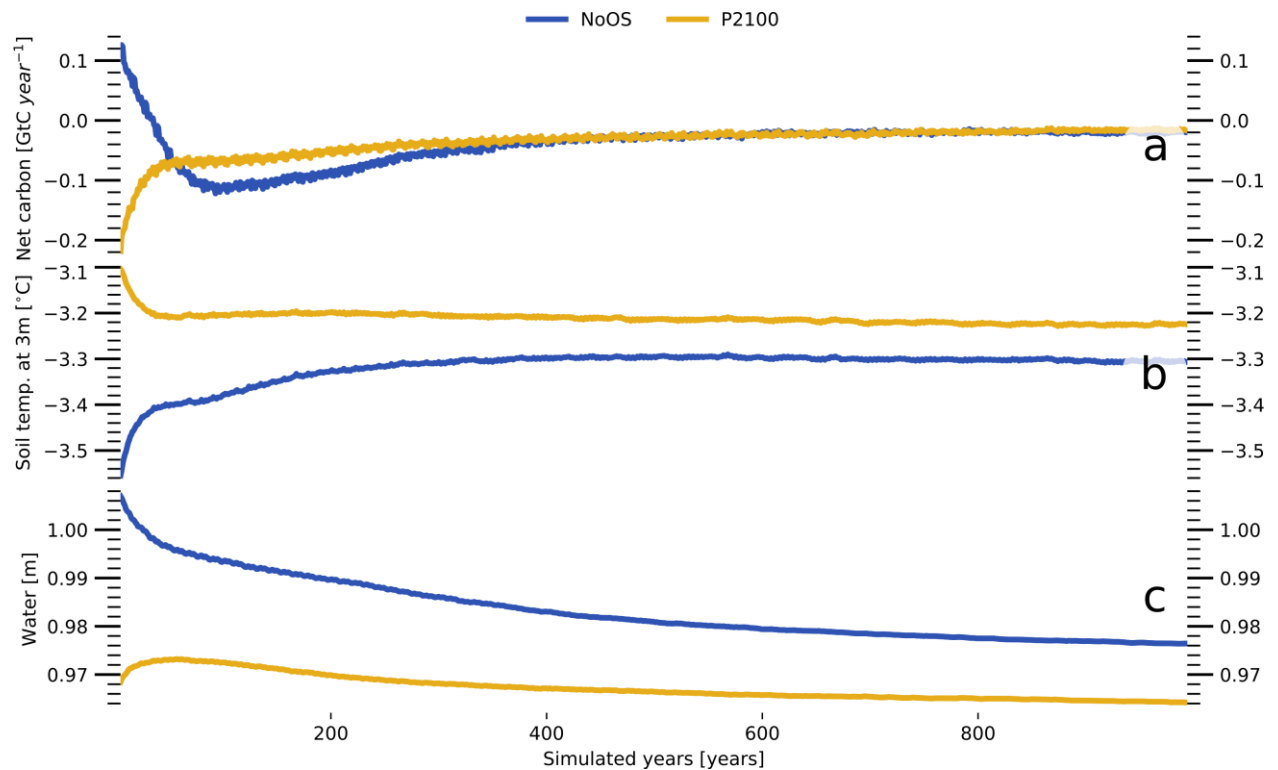
Results

Fig.4: Simulated dynamics preceding the period with steady atmospheric conditions: a) Simulated net ecosystem carbon fluxes into the atmosphere, b) soil temperatures at a depth of 3 m and c) total (liquid and frozen) water content of the soil – in the permafrost-affected areas of the high northern latitudes.



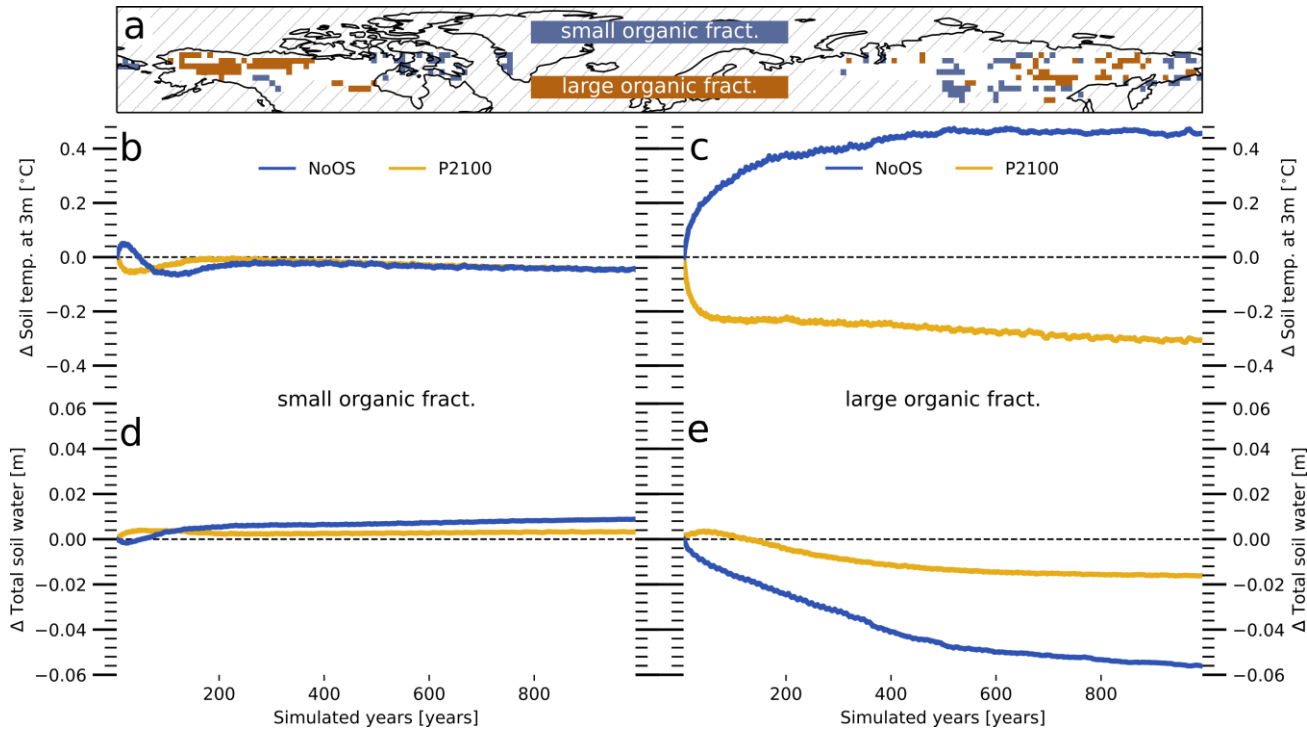
Arctic ecosystems exhibit a hysteresis-like behavior and the state of the soil as well as the terrestrial carbon fluxes depend on the preceding climate trajectory. Thus, soils are warmer and dryer and the terrestrial net carbon emissions are lower when climate stabilization happens subsequent to an temperature overshoot (P2100).

Fig.5: Development of key variables under the nontransient atmospheric conditions: a) Simulated net ecosystem carbon fluxes into the atmosphere, b) soil temperatures at a depth of 3 m and c) total (liquid and frozen) water content of the soil – in the permafrost-affected areas of the high northern latitudes.



Slow vegetation dynamics, long carbon turnover times and the large amounts of energy required for or released by the phase change of water lead to a large inertia in permafrost regions. Thus, it will take high latitude ecosystems several centuries to adapt to steady atmospheric conditions. Furthermore, there are notable differences between the scenarios even after 1000 years under the same atmospheric conditions, indicating overshoot-induced legacy effects that could sustain differing states over a much longer period.

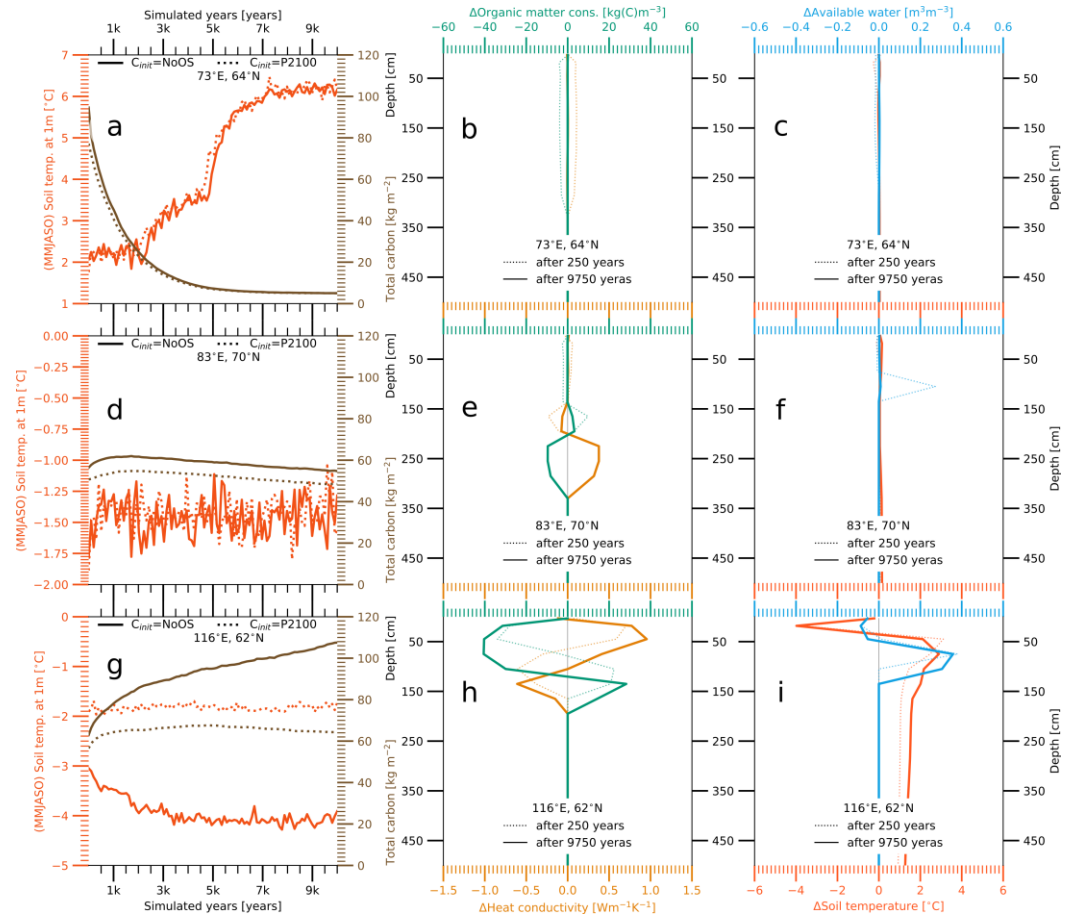
Fig.6: a) Grid cells that retain largely mineral (brown) or organic (blue) soils under the nontransient atmospheric conditions. b) Temperature development in grid cells that retain largely mineral soils. c) Same as panel b, but for organic soils. d) Same as panel b, but showing the total water content of the soil. e) Same as panel c, but showing the total water content of the soil.



With respect to the water- and energy cycle, the speed with which Arctic regions adapt to steady conditions is highly dependent on the properties of the soil, especially on the soil porosity. These are partly determined by the soil organic matter (SOM), which has a particularly high porosity. Thus, larger trends in temperature and water content are only present in soils that have a high SOM content while regions with predominantly mineral soils quickly adapt to the prevailing atmospheric conditions

Fig. 7: a,d,g) Simulated May-October-mean soil temperatures at a depth of 1 m and carbon densities for individual grid cells. Solid lines refer to a simulation which was initialized with soil carbon pools before the temperature overshoot (NoOS), whereas dotted lines show a simulation that started from the pools after the overshoot (P2100). b, e, h) Difference in soil organic matter concentration and heat conductivity between the two simulations (P2100-NoOS). c,f,i) Same as panels b,e,h but for the annual maximum soil temperature and liquid water content.

In grid-cells where the near-surface permafrost disappears under the nontransient conditions, the SOM, temperatures and water content converge on the same state, independent of the initial conditions (a,b,c). In contrast, in grid boxes that retain permafrost we often find long-lasting differences in the SOM between the two simulations. In some cases these differences are limited to the carbon content within the frozen fraction of the ground (d,e,f). But more importantly, we also find persistent, and even increasing, differences in the soil carbon concentration to coincide with sustained differences in the soil temperatures (g,h,i).



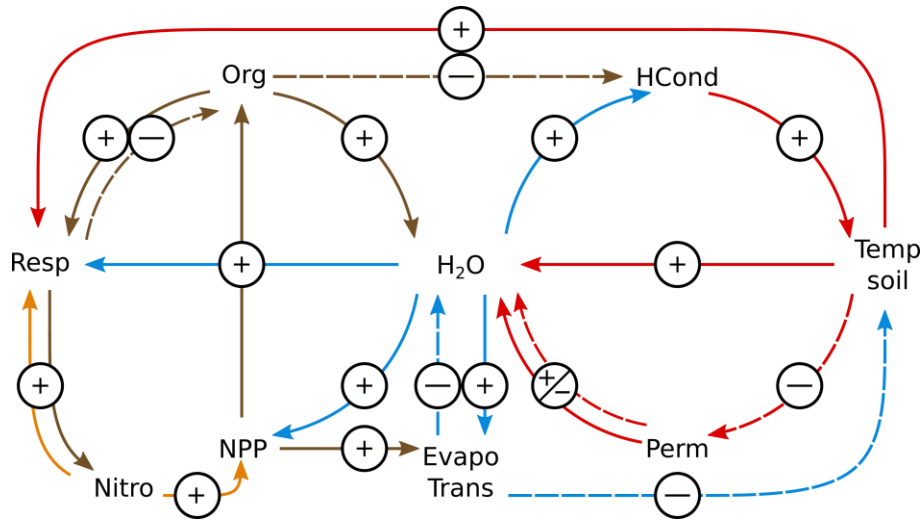
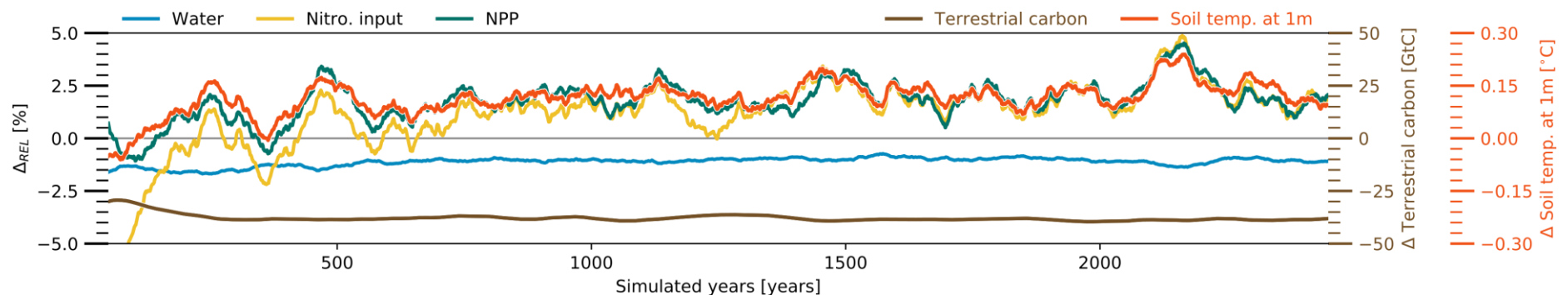


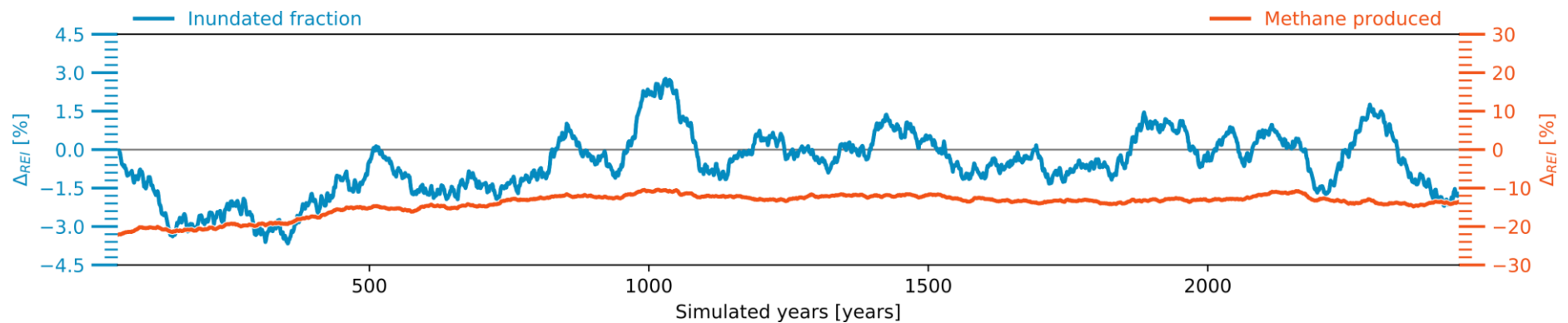
Fig.8: Dry organic matter (Org) has a lower heat conductivity (HCond) than mineral soil. Thus, high SOM concentrations inhibit the heat transport into the ground, decreasing soil temperatures (Temp soil) below the layers near the surface. The higher porosity of organic matter also increases the soil's water holding capacity and infiltration rates, which raises the water availability within the root-zone (H2O). This increases transpiration and evaporation rates (Evapotrans) and lowers water-stress related limitations on productivity (NPP). A higher productivity in turn entails larger carbon inputs and higher concentrations of organic matter in the soil. The increase in evapotranspiration decreases the Bowen ratio and leads to a substantial cooling at the surface which further reduces the heat flux into the ground. The lower soil temperatures can have diverging effects on the moisture content of the soil (H2O). Permafrost (Perm) acts as a barrier that inhibits drainage, resulting in a higher overall water contents. At the same time, lower temperatures lead to a smaller fraction water being liquid and available to plants and microbes. The result is that the plant available water predominantly increases, while deeper within the soil, a larger fraction of the water remains frozen over longer periods, inhibiting microbial decomposition (Resp). The smaller decomposition rates lower the availability of nitrogen (Nitro) as they reduce the nitrogen mineralization in the soil. This in turn limits productivity and, consequently, the carbon input into the soil which further reduces soil decomposition. On average, the effects of a reduced nitrogen availability outweigh the effects of the higher water availability. As a result the soil stabilizes not only at a higher soil organic matter concentration, but also at (predominantly) lower in- and outgoing carbon fluxes.

Fig.9: Differences between simulations initialized with the soil carbon concentrations after (P2100) and before (NoOS) an temperature overshoot that persist under nontransient atmospheric conditions. Shown are relative differences in total soil water content (blue line; left y-axis), inputs of mineral nitrogen (yellow line; left y-axis) and net primary productivity (green line; left y-axis) as well as absolute differences in total terrestrial carbon (soil organic matter and vegetation biomass; brown line; right y-axis) and MJJASO temperatures at a depth of 1 m (redline; right y-axis).



Irreversible legacy effects are not limited to a few grid cells, but they have a notable impact on the pan-Arctic scale. The average soil temperature differs by about 0.1 $^{\circ}$ C - 0.2 $^{\circ}$ C, the total soil water content, net primary productivity and soil respiration by about 1 % - 2.5 %, while the amount of total terrestrial carbon differs by about 40 GtC between the simulations with and without a temperature overshoot.

Fig.10: Differences between simulations initialized with the soil carbon concentrations after (P2100) and before (NoOS) an temperature overshoot that persist under nontransient atmospheric conditions. Shown are relative differences in annual-mean inundated area (blue line, left y-axis) as well as relative differences in the soil methane production (red line, right y-axes).



The effects of an overshoot are more pronounced in regions with high carbon densities. Thus, they are likely to have stronger impacts on processes that are more prominent in organic-rich soils, such as the soil methane production. Here, our simulations indicate that the overshoot has a comparatively small effect on the average wetland area, however, it reduces the overall soil methane production by around 10%, because it changes the correlation between inundated soils and large SOM concentrations.

How long until terrestrial Arctic adjusts to steady atmospheric conditions?

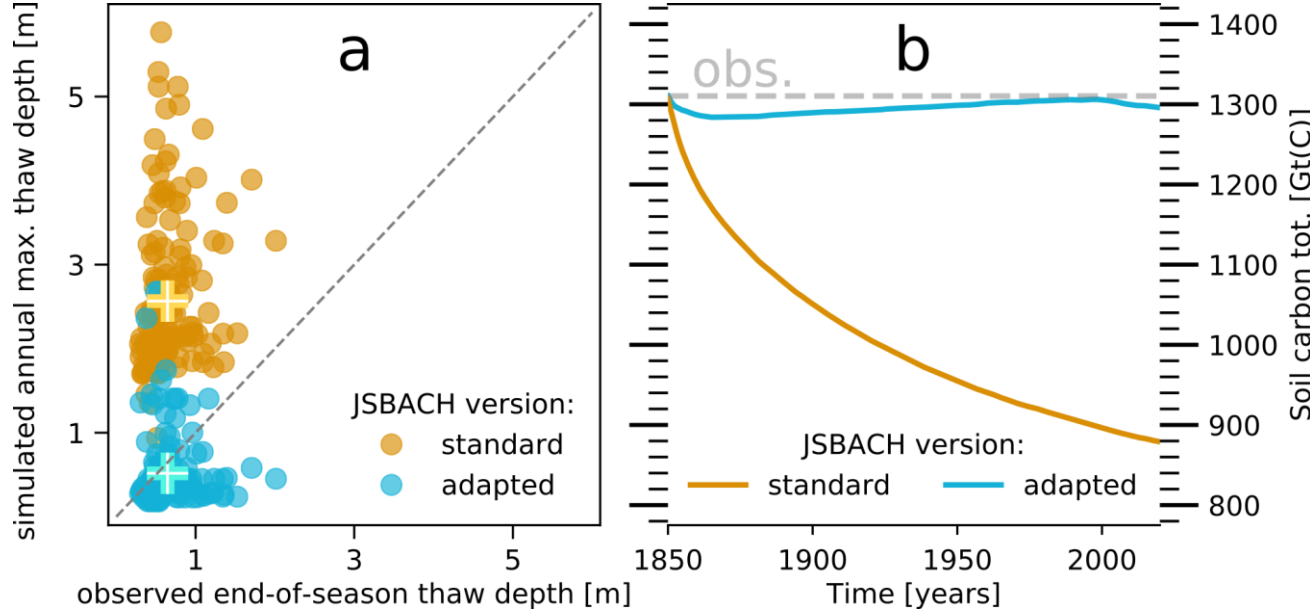
It takes the terrestrial Arctic several centuries to adjust to nontransient atmospheric conditions.

Does steady-state of high-latitude ecosystems depend on preceding climate trajectory?

Feedbacks between the water-, energy- and carbon cycles, allow for multiple steady-states in permafrost regions, which depend on preceding scenario.

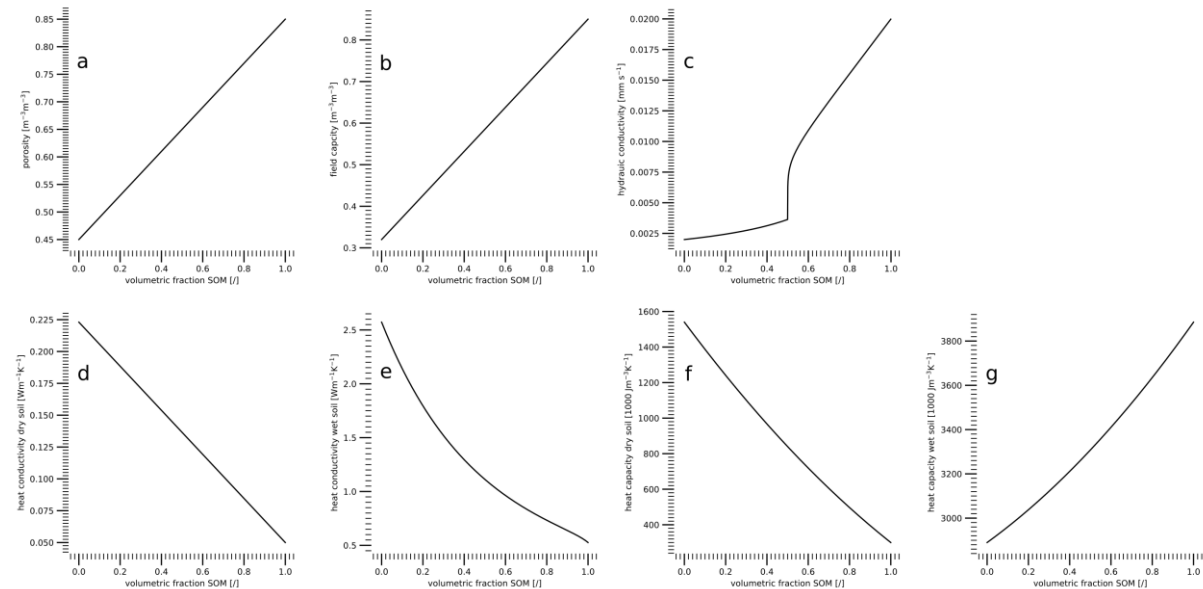
Details on JSBACH

Fig.11: a) Correlation between simulated and observed thaw depths for sites of the Circumpolar Active Layer Monitoring program (Brown et al., 2000). Brown dots indicate the maximum thaw depths simulated with the standard-model version, while blue dots refer to the adapted version used in the present study. Crosses show the average over all sites. b) Simulated soil carbon in the permafrost domain. The brown line refers to the standard JSBACH model, while the blue line shows the version used in the present study. Grey dashed line shows observation-based soil carbon stocks (de Vrese et al., 2021).



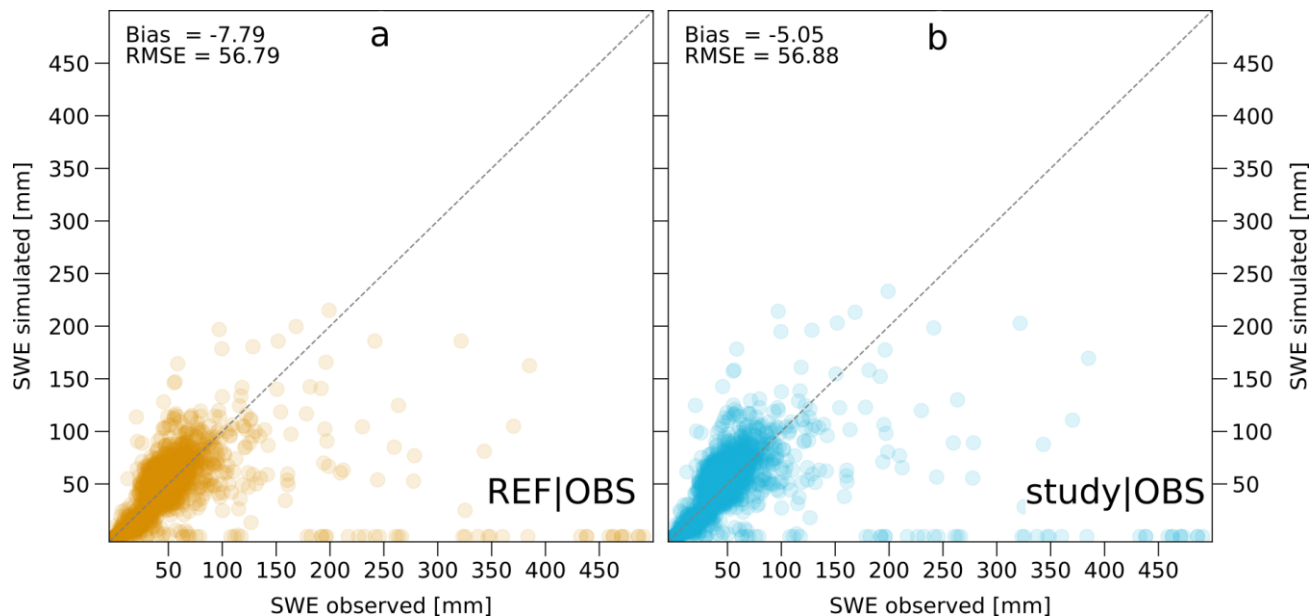
The standard JSBACH model includes a number of parameterizations that are not well suited for the specific conditions that are characteristic of the high latitudes. As a result, the standard model has certain shortcomings in the representation of the high-latitude energy, water and carbon cycle, such as a strong overestimation of the thaw depths and an inability to conserve the effectively inert organic matter contained in the permafrost. For the adapted model, we introduced a vertical distribution of the soil organic matter (including the vertical transport due to cryoturbation), which allowed us to calculate the decomposition rates based on the state of the soil as a function of depth. Furthermore, we account for the phase transition of water within the ground, which substantially reduces the amplitude of temperature fluctuations in the ground.

Fig.12: e-k) Examples of dependencies of soil properties on the SOM content (note that the actual values vary from grid cell to grid cell depending on the type of mineral soil). e) Porosity, f) field capacity, g) saturated hydraulic conductivity, h) heat conductivity of (completely) dry soils, i) heat conductivity of fully saturated soils, j) heat capacity of (completely) dry soils, k) heat capacity of fully saturated soils.



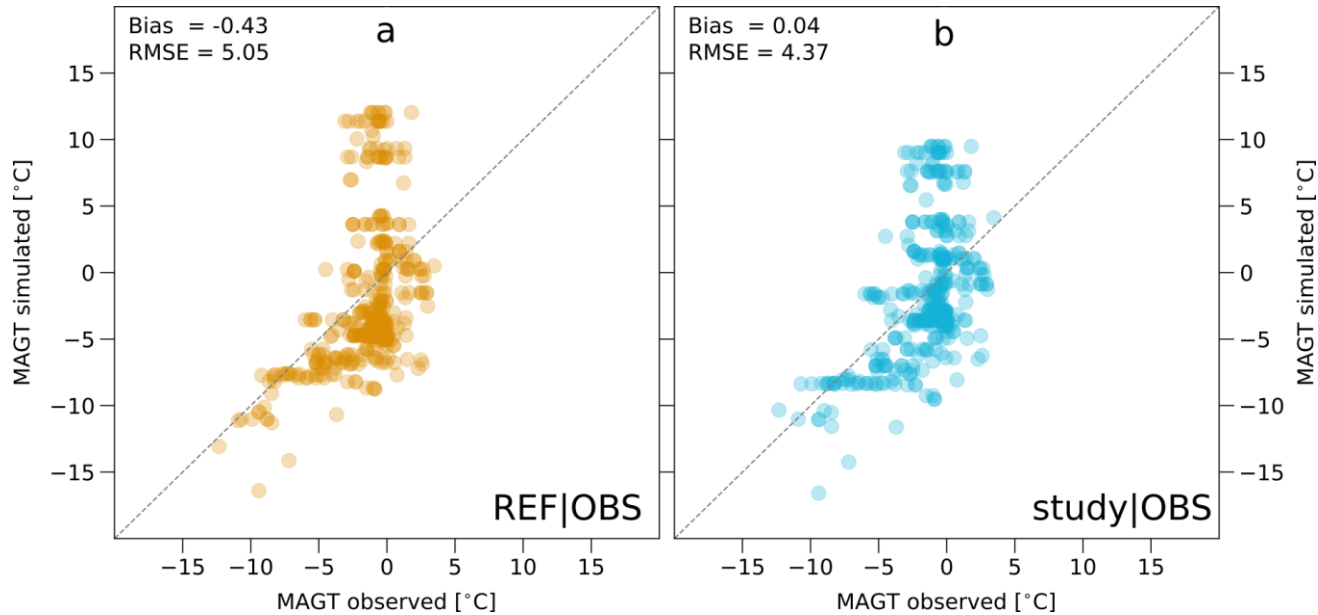
Besides accounting for the phase change in the soil, the adapted model version also determines important soil properties based on the water content of the soil, using formulations based on the approach proposed by Ekici et al. (2014). In addition the soil properties are also affected by the soil organic matter content enabling feedbacks between the carbon- and energy-cycles that allow for multiple steady states in the permafrost affected regions.

Fig.13: Comparison of simulated and observed snow water equivalent (SWE) in the northern high latitudes in grid cells north of 47.5°N for the period 1998 - 2012 . Observation-based data stems from the Northern Hemisphere subset of the Canadian Meteorological Centre operational global daily snow depth analysis (Brown & Brasnett, 2010). a) Observed and simulated SWE, for the standard JSBACH model. b) Same as panel a but for the setup used in the present study.



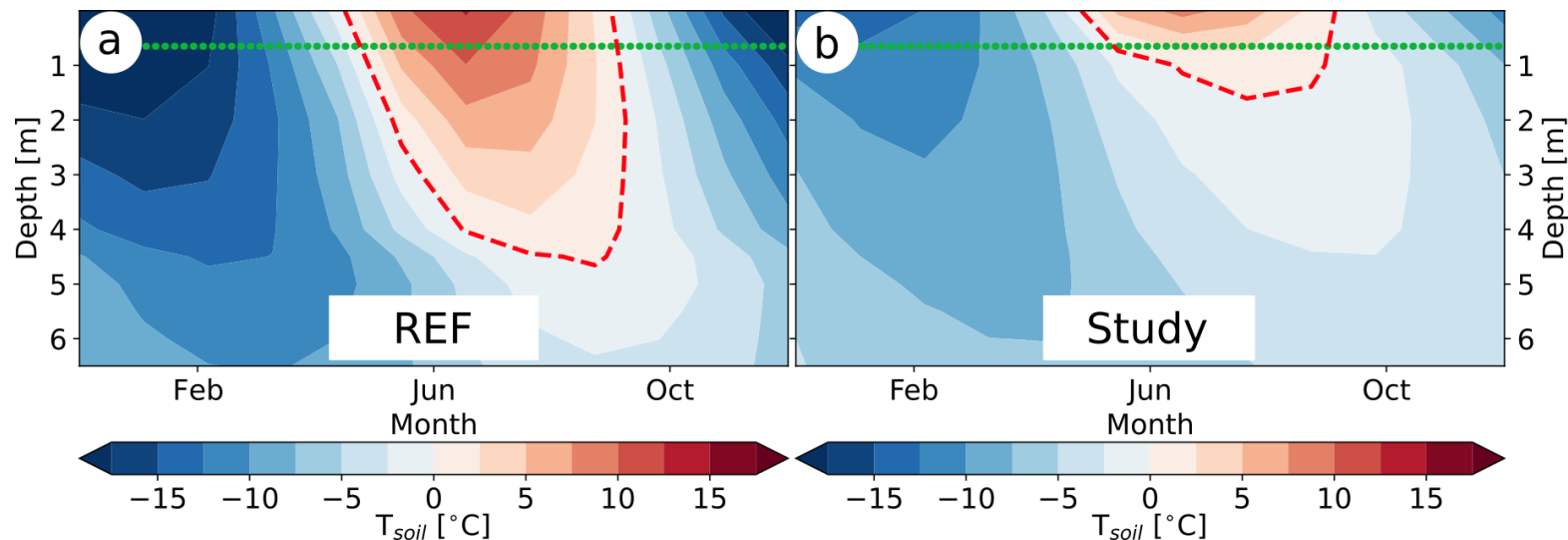
The simulated snow cover is largely determined by the precipitation rates and the simulated surface temperatures. Especially the later are captured well by the latest release of the MPI-ESM, thus also the simulated SWEs compare reasonably well with observations when the model is run with the forcing data derived from MPI-ESM model output. Nonetheless the standard model (a) over- and underestimates the SWE for individual grid boxes and that there is even a number of cells in which the model simulates no lasting snow cover, while the observations indicate a large SWE. There is no major improvement in simulations with the adapted model version even though the bias is slightly reduced.

Fig.14: Comparison of simulated and observed mean annual ground temperatures (MAGT), using data from the Global Terrestrial Network for Permafrost (Christiansen et al., 2010, Romanovsky et al., 2010, Smith et al., 2010). a) Comparison of MAGT and simulated annual mean soil temperatures at the lowest model level (10 m) for the standard JSBACH model. b) Same as a but for the model used in the present study (here, temperatures correspond to a depth of 11m).



For the standard model version (a), the simulated MAGT in the northern high latitudes are predominantly closer to the lower end of the observational range. For lower observed MAGTs ($MAGT < -5^{\circ}C$), the standard model systematically underestimates the temperatures, while MAGTs closer to the freezing point ($-5^{\circ}C < MAGT < 5^{\circ}C$) are similarly over- and underestimated. In simulations with the model version used in the present study (b), the lower MAGTs match the observations slightly better or rather they are less systematically underestimated. Furthermore, the partial over- and underestimation of MAGTs closer to the freezing point is reduced, resulting in a slightly better representation of the MAGT.

Fig.15: a) Simulated soil temperatures, using the standard JSBACH model, averaged across the northern permafrost regions, during the period 1990 – 2010. The (dashed) red line shows the position of the zero-degree-threshold and the (dotted) green line the observed end-of-the-season thaw depths averaged across the sites of the Circumpolar Active Layer Monitoring program. b) same as a, but for the adapted model.



When simulated with the standard model (a), the soil temperatures in the permafrost region exhibit a pronounced seasonal cycle throughout the entire soil column. Thus, temperatures during summer and fall are comparatively high and positive values reach (on average) beyond a depth of 4 m. As a result, the standard model overestimates the active layer thickness, despite the simulated mean annual ground temperatures being closer to the lower end of the observed range. In the adapted version (b), the amplitude of the annual temperature cycle is strongly reduced. Consequently, the soil temperatures during summer and fall are colder and, on average, positive values only extend to a depth of about 1 m.

Credits

Figures 1,2,4,5,6,12,13,14,15 and the associated texts were adapted from:

de Vrese, P. & Brovkin, V. Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios. Nature Communications, in press

, while figures 7,8,9,10 were taken from the same publication without modification. Figure 11 and the associated texts were taken from:

de Vrese, P., Stacke, T., Kleinen, T. & Brovkin, V. Diverging responses of high-latitude co2 and ch4 emissions in idealized climate change scenarios. The Cryosphere 15, 1097–1130 (2021).

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