Supplemental information to: Model simulations of arctic biogeochemistry and permafrost extent are highly sensitive to the implemented snow scheme

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S1 Adjusted respiration rate

We defined a new function following Natali et al. (2019), shown in Fig S1. The Q10 value was changed from the previous value of 200.5 to 2.9. Additionally, the minimum temperature threshold was set to -20 °C instead of the previously used -4 °C.

![Figure S1: The old and new function controlling respiration rate during cold conditions.](image)

S2 Site simulations

S2.1 Snowpack dynamics

Prior to the evaluation of the large-scale performance of the new, Dynamic snow scheme, we conducted a single-site comparison to examine the validity of the results. These detailed snow pack observations from Zackenberg helped to determine whether the Dynamic scheme can simulate internal snow pack dynamics, snow depth and snow density. We established the ability of the new snow scheme to simulate snow conditions by comparing a simulated snow pack with snow depth and density observations from Zackenberg (2013-2014 snow season). Figure S2 presents the observed and simulated snow pack by the Dynamic and Static schemes. This figure shows that the Dynamic scheme simulates higher snow depth due to lower density values in the mid and top layers of the snow pack. Density values are compared qualitatively, since it is difficult to accurately align the observational and modelled layer densities.
Thermal properties in snow layers are derived from density, and this entity is especially important in the *Dynamic* snow scheme. The comparison to observations shows that the modelled density compares well to observations. There are lower densities early in the snow season and fresh snow has a low density, while density increases in late spring during the melt season. The *Static* scheme with constant snow density simulated a somewhat higher than observed snow depth. The difference in snow depth between the *Static* and *Dynamic* simulations is small - as indicated in Fig. S2, bottom panel.

![Figure S2: Snow pack dynamics at the Zackenberg GeoBasis station. Density values for the layers are extrapolated - from three and five layers for the observational and modelled data, respectively. The colours of the snow pack indicate snow density.](image)

Overall, the new scheme reproduces the snow dynamics over the cold season better than the *Static* scheme. Please note that the model’s climate forcing is a crucial controlling factor when simulating snow conditions. For this study, we used a global climate forcing dataset, which may explain some of the observed model-observation differences. Taken together, these results suggest that the *Dynamic* scheme is skilled in simulating the snow pack’s internal structure and dynamics. Since the *Static* scheme has a constant snow density throughout the snow season, the *Dynamic* scheme is expected to better capture the seasonal behaviour of snow and soil conditions. The Zackenberg site comparison indicated that the *Dynamic* scheme successfully integrated these key processes affecting the density over the snow season. The mismatch between snow observations and simulations is influenced by the use of a global model forcing dataset instead of site-specific temperature, precipitation or snowfall series.
S2.2 Site simulation details

Years of observational data used for the site simulations on Abisko, Bayelva, Kytalyk, Samoylov and Zackenberg sites (PAGE21 sites) can be seen in Table S1. The computed RMSE between observed and modelled near surface soil temperature and air-soil temperature difference is shown in Table S2.

Table S1: Snow depth and near surface soil temperature data used for the site simulations, and climatic zones of the sites. (Sect.3.1)

|                | Abisko      | Bayelva     | Kytalyk     | Samoylov    | Zackenberg |
|----------------|-------------|-------------|-------------|-------------|------------|
| snow depth     | 1986-2020   | 1998-2009   | 2011-2013   | 1996-2013   | 1996-2011  |
| soil T         | 2012-2015   | 1998-2017   | 2004-2011   | 2012-2014   | 1995-2017  |
| climatic zone  | sub-arctic  | high arctic | low arctic  | low-arctic  | high arctic|

Table S2: RMSE for soil temperature and ∆ T for the applied snow schemes, and temperature regimes at the Russian sites (Sect. 3.2).

|                | -15 °C < $T_{air}$ < -5 °C | -25 °C < $T_{air}$ < -15 °C | $T_{air}$ < -25 °C |
|----------------|-----------------------------|-------------------------------|---------------------|
| Soil T (°C)    | Static                      | Dynamic                      | RMSE (°C)           |
|                | 6.36                        | 0.65                         | 12.61               |
|                | 0.65                        | 1.26                         | 18.14               |
| ΔT (°C)        | Static                      | Dynamic                      | RMSE (°C)           |
|                | 6.98                        | 1.1                          | 12.29               |
|                | 1.1                         | 0.96                         | 19.28               |
S3 Pan-Arctic simulations

S3.1 Seasonal cycle of variables

Seasonal cycles of snow depth, upper soil column water content, NEE and NPP series for the Dynamic and Static simulations. Differences are calculated by subtracting the Static from Dynamic simulation outputs.

Figure S3: Seasonal dynamics of snow depth, soil temperature (25 cm depth) and fractional water content, (b) seasonal NEE and NPP.
S3.2 Simulated physical variables

These figures show the spatial pattern of simulated variables averaged over 1990-2015. Summer season values are averaged over June, July and August and winter season values are averaged over December, January and February.

Figure S4: Simulated snow depth using the Static and Dynamic snow schemes and their difference.

Figure S5: Simulated maximum annual active layer depth (ALD) using the Static and Dynamic snow schemes and their difference.
Figure S6: Simulated near surface soil temperature (25 cm depth) using the Static and Dynamic snow schemes and their difference for winter and summer.
S3.3 Simulated biogeochemical variables

Figure S7: Simulated heterotrophic respiration normalised by soil carbon content, using the Static and Dynamic snow schemes and their difference for winter and summer.
Figure S8: Simulated NPP using the Static and Dynamic snow schemes and their difference for winter and summer.
S3.4 Nitrogen cycling

Besides the carbon-related fluxes, we also assessed the impact of snow on nitrogen cycling. Figure S10 shows the nitrogen mineralisation (Fig. S10 (a)) and leaching (Fig. S10 (b)) normalised by soil carbon content. Nitrogen mineralisation only changed markedly during the summer season within the permafrost region. Leaching is higher for the Dynamic scheme in Eastern-Canada and Northern-Russia. Nitrogen use efficiency (NUE) on panel (c) was calculated as the ratio between NPP and nitrogen uptake. The Dynamic scheme simulates a lower NUE than the Static scheme, which indicates a higher N uptake per unit productivity.
Figure S10: Nitrogen mineralisation, N leaching and NUE difference calculated by subtracting the Static from Dynamic simulation outputs.

Table S3: Pan-arctic mean values for the studied variables for the Static and Dynamic simulations, and their respective differences.

| variable         | unit | Static | Dynamic | Dynamic-Static | note of changes     |
|------------------|------|--------|---------|----------------|---------------------|
| snowdepth        | m    | 0.22   | 0.3     | 0.06           | general increase    |
| ALD              | m    | 0.98   | 1.05    | 0.07           | increase in ALD     |
| soilT<sub>winter</sub> | °C   | -22.6  | -12.5   | 10.16          | increased in T      |
| soilT<sub>summer</sub> | °C   | 6.3    | 4.3     | -2.0           | decrease in T       |
| GPP<sub>winter</sub> | g m<sup>-2</sup> | 0.14   | 0.2     | 0.04           | increase in gross production |
| GPP<sub>summer</sub> | g m<sup>-2</sup> | 221.1  | 211.6   | -9.4           | decrease in gross production |
| NPP<sub>winter</sub> | g m<sup>-2</sup> | -3.0   | -5.2    | -2.1           | decrease in productivity |
| NPP<sub>summer</sub> | g m<sup>-2</sup> | 156.2  | 146.3   | -9.8           | decrease in productivity |
| Rh<sub>winter</sub> | g m<sup>-2</sup> | 2.5    | 7.7     | 5.3            | increase in Rh     |
| Rh<sub>summer</sub> | g m<sup>-2</sup> | 116.8  | 93.1    | -24.7          | decrease in Rh     |
| NEE<sub>winter</sub> | g m<sup>-2</sup> | 5.5    | 13.0    | 7.4            | increased carbon emission |
| NEE<sub>summer</sub> | g m<sup>-2</sup> | -38.3  | -53.2   | -14.9          | increased carbon uptake |
| soilC            | kg C m<sup>-2</sup> | 11.1   | 10.2    | -0.97          | decrease in soil C  |
| vegC             | kg C m<sup>-2</sup> | 1.9    | 1.9     | 0.06           | marginal difference |
Figure S11: Mean fractional water content of the upper soil column in April, May, June and July, using the Static, Dynamic schemes and their difference.
S3.5 Vegetation dynamics

Sites where PFT dominance changed between the Static and Dynamic simulations is shown in Fig. ???. These transition sites are scattered across the Arctic, but there are some clear hotspots in Eastern-Russia, the Scandinavian coastline and Northern-America.

Figure S12: (a) Direction of dominant vegetation group changes between the Static and Dynamic schemes. The size of arrows show the number of sites transitioning. (b) Spatial distribution of sites where PFT dominance changed between the simulations.

References

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