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Key Points:

- Winter warming events (WWEs) have increased in the Arctic and are expected to increase further, but their impacts are not thoroughly evaluated in large-scale ecosystem models.
- We applied different scenarios of enhanced WWEs in a widely used ecosystem model, LPJ-GUESS, and found that their impacts on ecosystem processes could be substantial and of magnitudes comparable to those of altered winter climatologies.
- The direction of the modeled WWE impacts on ground temperatures differed from what the observation-based literature suggests, and we identified essential processes lacking in LPJ-GUESS that may cause this mismatch.

Abstract

Winter warming events (WWEs) are short-lasting events of unusually warm weather, occasionally combined with rainfall, which can cause severe ecosystem impacts by altering ground temperatures and water fluxes. These impacts are generally overlooked in large-scale ecosystem models. The frequency and intensity of WWEs will likely increase further in the future. We used an ecosystem model, LPJ-GUESS, to investigate the responses of four subarctic ecosystems to different levels of predicted WWEs, and identify model gaps hindering accurate estimates of these responses. In response to WWEs, the model simulated substantial ground cooling (up to 2 °C in winter) in contrast to the observed warming, leading to changes in biogeochemical fluxes often comparable in magnitude to those from altered winter climatologies. The mismatch between the modelled and the observed ground temperature changes may be due to the 1) lacking surface energy balance, 2) daily timestep, and 3) simplistic water retention scheme in LPJ-GUESS.

**Plain Language Summary**

In the Arctic, winter warming events (WWEs) are episodes of exceptionally warm weather that last from hours to a few days and often occur in combination with rainfall. The combined effect of multiple processes triggered by WWEs (involving, for example, changes in snow depth and snow properties,

and heat exchanges between air, rain and meltwater, and soils) results in profound changes in ground temperatures and water fluxes, which many ecosystem processes depend on (vegetation dynamics, organic matter decomposition by microbes, etc). However, large-scale ecosystem models, which are used to study how arctic ecosystems will change in the future, often overlook the effects of WWEs because they oversimplify some complex physical processes and operate at longer temporal scales than WWEs. WWEs will likely become more frequent and intense in the future as the climate continues to warm. This study used a widely used ecosystem model, LPJ-GUESS, to investigate how the ecosystems will respond to more frequent and intense WWEs. The ecosystem responses that we observed were notable but in the opposite direction as observed in field measurements. We identified the processes that are lacking in the model and are causing this mismatch which, if implemented in the model, would significantly improve the predictions of future ecosystem changes in response to climate change.

## 1 Introduction

The Arctic is warming three times faster than the global average, with the strongest warming occurring in autumn and winter (AMAP 2021). The occurrence and impacts of winter warming events (WWEs), i.e. short-lasting extraordinarily warm spells, often accompanied by rainfall (rain on snow; ROS), are increasing rapidly and expanding geographically (e.g. Bartsch et al., 2010; Vikhamar-Schuler et al., 2016; Pan et al., 2018). Climate models predict a further increase in the coming decades. Despite their short duration, these extreme events could cause societal and environmental impacts that can override the impacts of long-term climatic trends (e.g., Phoenix & Bjerke, 2016).

In the winter, the impacts of WWEs are currently considered a research priority for better understanding future ecosystem dynamics in the subarctic (Pascual et al., 2020). WWEs can affect ground temperatures (GT) in multiple ways, mostly through: (1) direct heat transfer from the air, (2) latent heat release from refreezing melt and rainwater, and (3) changing the snowpack properties, such as depth and density, which influence the energy exchanges between the atmosphere, snow, and soil. These altered winter processes can further influence ground albedo and groundwater content (GWC), which has impacts lasting to the growing seasons (Pascual & Johansson, 2022). These WWE-associated environmental changes can further alter microbial activity, greenhouse gas (GHG) emissions (e.g., Natali et al., 2019), and permafrost and vegetation dynamics (Bruhwiler et al., 2021), ultimately altering the arctic carbon budget.

These interlinked processes and feedbacks related to WWEs are difficult to disentangle in observational data and thus challenging to implement in models. Moreover, large-scale ecosystem models which run with monthly climate data do not explicitly account for the impacts of such stochastic climate extremes (e.g. Tang et al., 2015).

In this study, we investigate the potential effects of predicted WWE scenarios

on winter and growing-season physical and biogeochemical variables using the latest version of a widely used dynamic ecosystem model, LPJ-GUESS. We aim to evaluate the model’s performance and identify model gaps in representing ecosystem responses to future WWEs.

## 2 Materials and Methods

### 2.1 Study sites

The Torneträsk area, in northern Sweden, is a topographically heterogeneous area that aligns along a strong west-east oceanic-continental climatic gradient, with precipitation and winter temperature decreasing eastwards due to the increasing continentality and the rain shadow effect caused by the Scandes Mountains. The area has experienced rapid climate warming (Callaghan et al., 2010) and a substantial increase in the frequency and intensity of WWEs (Pascual & Johansson, 2022).

Vegetation in the area varies following its climatic and altitudinal gradients. Birch forests occur below c. 600 and 800 m.a.s.l (Van Bogaert, 2010). Tundra species dominate above the tree-line, while in the lowlands, birch forests alternate with peat plateaus underlain by permafrost, and non-permafrost fens.

In this modelling study, we selected four sites representing these dominant ecosystem types in the Torneträsk area, including (1) a birch forest (~370 m.a.s.l) located <10 km east of the Abisko Station (ANS) (Heliasz et al., 2012); (2) a tundra site (~410 m.a.s.l), located <1 km to the southeast of the ANS (Michelsen et al., 2012 and references therein); (3) a peat plateau (~380 m.a.s.l) known as Storflaket, located c. 6 km east of the ANS (Johansson et al., 2013), and (4) a fen (~515 m.a.s.l) located c. 25 km west of the ANS, near the Katterjokk Station (SMHI). The dominant vegetation species at these sites are found in Appendix A.

### 2.2 Model description and simulation setup

#### 2.2.1 Model description

The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) is a process-based dynamic ecosystem model widely used on regional and global scale studies (Smith et al., 2001; 2014). The model simulates vegetation dynamics (including vegetation establishment, mortality and competition, etc.), water, carbon and nitrogen cycles, and soil biogeochemistry. This study used the latest version of LPJ-GUESS (version 4.1, Smith et al., 2014), with the recently-developed dynamic, intermediate complexity snow scheme enabling the simulation of climate-snow-soil interaction. The model can simulate up to five snow layers, their physical and thermal properties, and their development throughout the cold season. Based on the individual snow layer properties (e.g., temperature, density, thermal conductivity), freeze-thaw processes in snow layers, and heat transport through the snowpack between the atmosphere and soil can be simulated, and ROS events can be accounted for (Pongracz et al., 2021). LPJ-GUESS includes detailed representations of permafrost and

wetland processes, including peatland hydrology, peatland-specific PFTs, and CH<sub>4</sub> emissions (see Wania et al., 2009a, 2009b, 2010).

### 2.2.2 Model setup

Daily climate data provided by the ANS (ANS 2020) and Katterjokk Station (SMHI), including air temperature, air temperature daily range, and precipitation, together with shortwave radiation (1913-1984, Sheffield et al., 2006; 1984-2018, ANS) and annual CO<sub>2</sub> concentrations obtained from the Global Monitoring Laboratory (<https://gml.noaa.gov/ccgg/trends/>), were used to drive the model from 1913 to 2018. Soil property data was extracted from the WISE5min, V1.2 Soil Property Database (Batjes 2012). More details about the setup and input data are found in Appendix B.

Representative plant functional types (PFTs) were selected for each site (Table A1). We enabled high-latitude and wetland-specific plant functional types (PFTs) in the simulations to better capture site-specific vegetation conditions (see Wania et al., 2009 for more details). The PFT parameters at each site followed previous studies (e.g., Tang et al., 2015; Gustafson et al., 2021) (Table A2).

### 2.2.3 Model calibration and evaluation

Sobol sensitivity analyses (SA) were conducted to explore the influence of different parameters and parameter interactions on the estimated seasonal snow density, snow depth, snow temperature, and GT at the study sites (except for the tundra site due to lack of observational data for calibration and evaluation) (Appendix D). A sampling of eight relevant parameters, using ranges based on literature values, and a certain percentage of changes from the original values (Table D1), was conducted. Among the most influential parameters, we selected the parameter values that minimized the absolute differences between the measured and the modeled seasonal snow depth and GT at each site (2006-2012 at the peat plateau, 2001-2010 elsewhere) (Figures D4-8). The model was subsequently evaluated with independent observational data (2011-2018) when possible (Appendix E).

### 2.2.4 Model simulations with future WWEs

We generated manipulation experiments with different levels of WWE frequencies and intensities imposed on the observation-based climate inputs (HISTORICAL dataset) to assess the responses of different ecosystem processes to these extreme events. The applied frequencies and intensities were based on different climate scenarios in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). We selected six climate scenarios from two general circulation models (GCMs) with different climate sensitivities, i.e., CanESM5 and GFDL-ESM4, and three shared socioeconomic pathways representing three levels of varying GHG projections, i.e., SSP119, SSP270, and SSP585. For each scenario (n=6), daily meteorological data (1950-2100) for the gridcell near the Torneträsk area was extracted, and then bias-corrected at a daily scale. De-

tailed descriptions of the CMIP6 scenarios and the bias-correction method are found in Appendix C.

The bias-corrected GCM’s outputs were used to create the manipulation experiments (Table 1). In addition to the HISTORICAL runs (S0), we designed three additional experiments in which the future monthly anomalies in the frequency and intensity of melt days (S1), ROS (S2), and both (S3) in the GCM’s outputs (Table C2) were added to the HISTORICAL climate inputs, maintaining the long-term climate means as unchanged as possible. These anomalies were calculated based on four indices modified from Vikhamar et al. (2016) (Table C1).

The effects of altered WWEs and those from the altered long-term climate trends were compared by using an additional experiment (S4) in which the future winter monthly anomalies (Table C3) were directly added to the historical daily air temperature and precipitation.

**Table 1.** *Description of the HISTORICAL and MANIPULATION runs.*

| Simulation names | Description                                                                                                                                             |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| S0               | HISTORICAL scenario                                                                                                                                     |
| S1               | Altered melt days frequency (WWE index 1 = n days with $T > 0^\circ$ ) and intensity (WWE index 2 = n days with $T > 0^\circ$ and $P > 1$ mm)           |
| S2               | Altered ROS frequency (WWE index 3 = n days with $T > 0^\circ$ , and $P > 1$ mm) and intensity (WWE index 4 = n days with $T > 0^\circ$ and $P > 1$ mm) |
| S3               | Altered frequency and intensity of both melt days and ROS (indices 1, 2, 3 & 4)                                                                         |
| S4               | Altered winter climatologies                                                                                                                            |

Note. T and P refer to air temperature and precipitation. The monthly anomalies were calculated for November to March based on periods of 2071-2100 and 1985-2014.

### 3 Results and discussion

#### 3.1 Sensitivity analyses and model calibration

The Sobol indices showed that the dens\_min (minimum snow density) and compaction\_rate (the rate at which snow is compacted over time), and their interactions, mainly influence the modelled seasonal snow depth, snow density, snow temperature, and GT (Figure D1-3).

The parameter values yielding the lowest measured-modelled differences in seasonal snow depth and GT are 50, 60, and 90 for dens\_min, and 0.5, 0.8, and 0.9, for compaction\_rate, at the birch forest, peat plateau, and fen sites, respectively (Figure D4-8).

For the tundra site, we applied parameter values of 90 and 0.8 for minimum snow density and compaction rate, as these showed the best agreement with the available growing-season observational data.

#### 3.2 Evaluation of physical and biogeochemical variables in the historical period

### 3.2.1 Evaluation of physical variables

The seasonal patterns of snow cover were captured in the model at all sites. However, snowpack depth was considerably underestimated at the birch forest and the low-elevated fen site, but overestimated in low vegetation settings such as the peat plateau (Figure E1), likely due to the model lacking lateral transport and trapping/deposition of wind-blown snow. This mismatch affected the snow insulating capacity and caused substantial cold and warm biases in winter GT in the birch forest and peat plateau, respectively, but not in the fen (Figure E2) where the modelled snowpack depth exceeds the depth of the maximum insulating effect (40 cm; Zhang, 2005). The growing season GT was well captured at the birch forest and fen sites, but was underestimated in the peat plateau (Figure E2a,c,d).

The model was able to simulate short-term fluctuations in snow depth and GT during WWEs at all sites, but not their magnitudes (Figure E3). At the birch forest and peat plateau, larger than measured fluctuations in GT were modeled during WWEs and these differences were much smaller in the late winters. The modelled differences were largely linked to the simulated insulating capacity of snowpacks. Noticeably, stronger modeled reductions in snow depth occurred during early- and mid-winter WWEs, when the energy needed to warm-up and subsequently melt the thin and fresh (less dense) snowpacks is smaller. The modeled and measured GTs at the fen site remained around 0 °C throughout the winter due to the strong insulation of the thick snowpack, but the model captured the observed snowpack responses to WWEs.

### 3.2.2 Evaluation of biogeochemical variables

The modeled maximum LAI of 1.6 and 1.5 fell within the observed ranges at the birch forest (Heliasz, 2012) and tundra sites (Simin et al., 2021). Following the biases in GT, winter CO<sub>2</sub> heterotrophic respiration ( $R_h$ ) was underestimated at the birch forest and overestimated at the peat plateau (Figure E4). We speculate an overestimation of winter  $R_h$  at the tundra –it presents similar winter  $R_h$  values than the fen and peat plateau, and 6-fold larger than the birch forest– due to the overestimated soil C pool at this site. The model underestimated the growing-season ecosystem respiration ( $R_{eco}$ ) and gross primary production (GPP) in the tundra (Figure E5c,d). At the birch forest, the model predicted a strong annual C sink in 2007-2010, but measurements indicated a fairly neutral C balance (Figure E4a,b). At the peat plateau and fen sites, the model captured the annual fluctuations and magnitudes of CO<sub>2</sub> fluxes (Figure E4c-f). Across four sites the model was unable to capture the observed strong C source in September.

The differences in CH<sub>4</sub> fluxes between the peat plateau and fen sites were well captured by the model. However, the model underestimated by 55% the winter CH<sub>4</sub> fluxes at the peat plateau, likely due to the colder bias in modeled GT (Figure E6a,b).

### 3.3 Effects of enhanced WWEs

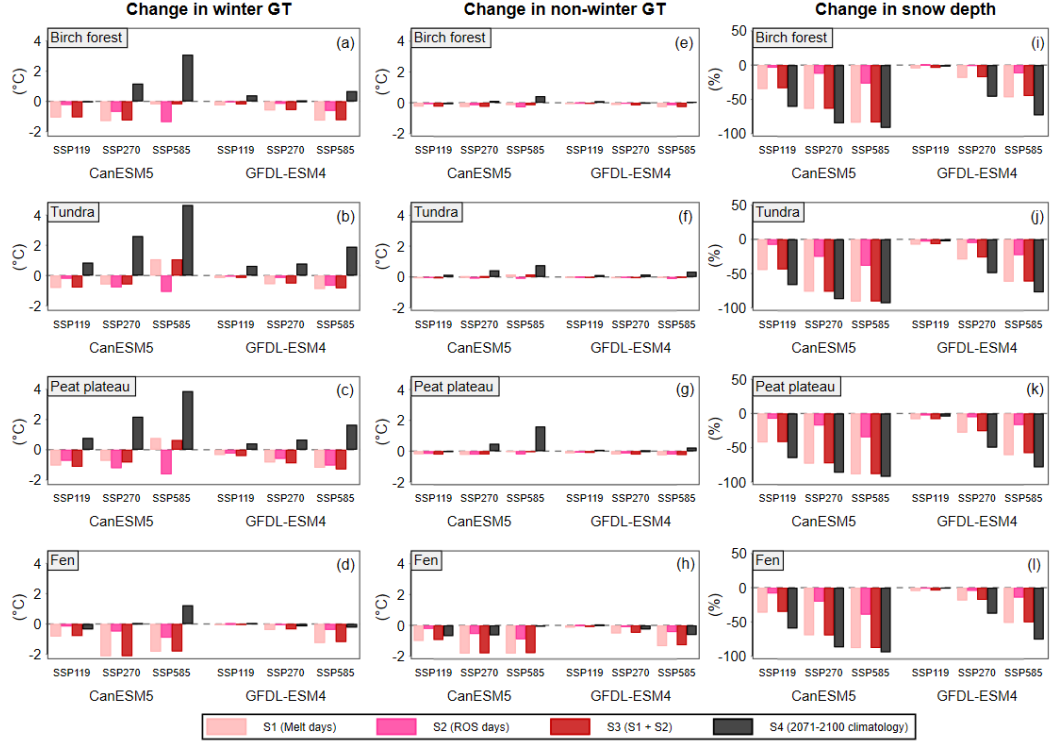
#### 3.3.1 Impacts on physical variables

The WWE experiments (S1-S3) caused an overall reduction in winter GT (up to 2 °C) in all ecosystem types, except for the runs driven by WWEs from CanESM5 SSP585 at the tundra and the peat plateau (Figure 1a-d). The modeled snow depth also decreased substantially under all WWE experiments. This might suggest that the major driver of the modelled WWE effects on winter GT is snow insulation, which decreases as a combination of the snowpack depth reduction, and the increased thermal diffusivity (caused by higher thermal conductivity and lower heat capacity after freeze-thaw processes), facilitating the heat exchange between atmosphere and soil (Figure 3). However, a “tipping point” may be crossed above a certain WWE magnitude, when the strong cooling effects of the reduced snow insulating capacity are counteracted by the stronger warming effects of longer and more extreme WWEs. This point is reached faster under shallow snowpacks where snow insulation is weak and its further reduction has a smaller effect on GT compared to the overall warmer conditions.

In contrast to WWEs, altered future winter climatologies (S4) increased the modeled winter GT at all sites, from less than 1 °C to as much as 4 °C at the birch forest, tundra, and peat plateau in the warmest scenario, i.e., CanESM5 SSP585, despite snowpack reductions of >80%. The modeled GT warming effect diminishes under thick snowpacks, due to the snow insulation-related process described above: at the fen site (thickest snowpack) we can only see a GT warming under CanESM5 SSP585.

Our results agree with the modelling results by Beer et al., (2018), who suggested that WWEs may cause GT cooling mainly by reducing the snowpack depth. However, there is increasing observational evidence that intense ROS events cause substantial and long-lasting GT warming in winter (e.g., Hansen et al., 2014) through the latent heat released from refreezing of infiltrated water at the bottom of thick snowpacks (Westermann et al., 2011; Pascual et al., 2022). This long-lasting GT warming cannot be captured in LPJ-GUESS due to the lack of essential processes describing the energy and water exchanges between the atmosphere, snowpack, and soil (Figure 3).

In non-winter, the impacts of the manipulation experiments on GT followed those seen for winter GT, although smaller in magnitude (Figure 1e-h). The WWE impacts on non-winter GWC (0-50 cm depth) were marginal except for the fen site (decrease of up to  $0.3 \text{ m}^{-3} \text{ m}^{-3}$ ) (Figure F1). GWC affects the thermal properties of soils, and its reduction likely contributed to the larger non-winter GT cooling modeled at the fen. The reduced albedo following an earlier snow cover disappearance can contribute to faster GT warming in spring, but this process is not represented in the current version of LPJ-GUESS.



**Figure 1.** Differences between the MANIPULATION runs (S1-S4) and the HISTORICAL runs (S0) for winter GT (°C; left column), non-winter GT (°C; middle column), and winter snow depth (%; right column), at each site.

### 3.3.2 Impacts on biogeochemical variables

Our results further showed large WWE-induced impacts on all biogeochemical variables, with magnitudes often comparable to impacts deriving from altered winter climatologies (Figures 2 and G3). GT and water availability are key drivers of the ecosystem C cycle, as they influence the start of the growing season, nutrient availability, vegetation dynamics, and soil  $R_h$ .

The modelled impacts of the manipulation experiments on biogeochemical variables generally followed the same direction as those observed for GT and GWC. We noted substantial reductions in GPP (Figure 2i-l) under the WWE experiments S1 and S3 of up to 25% at the fen, 20% at the peat plateau, and 10% at the birch site, and smaller reductions under ROS events alone (S2). The tundra site showed weaker reductions in GPP than the other sites, ranging from a few percent to up to 5% in the milder WWE experiments (driven by SSP119), and increases of up to 10% under CanESM5 SSP585. In contrast, for S4, the model simulated weak changes in GPP in the mildest CMIP6 scenarios, but sizable



increases in GPP in the CanESM5 SSP585: up to 75% in the peat plateau, c. 50% in the birch forest, c. 25% in the tundra, and c. 10% in the fen site. The impacts on  $R_a$  mirrored those described for GPP (Figure 2e-h). Noticeably, the relationship between GT, and both GPP and  $R_a$ , is not linear because the processes involved in plant dynamics are multiple and complex. For example, observational and manipulation studies have reported considerable vegetation damage, delays in bud phenology, and reductions in vegetation greenness due to phenological and frost stress following WWEs (Bokhorst et al., 2009, 2010). These impacts on vegetation are not explicitly represented in the model, as it does not yet take into account these winter/spring stress-related processes.

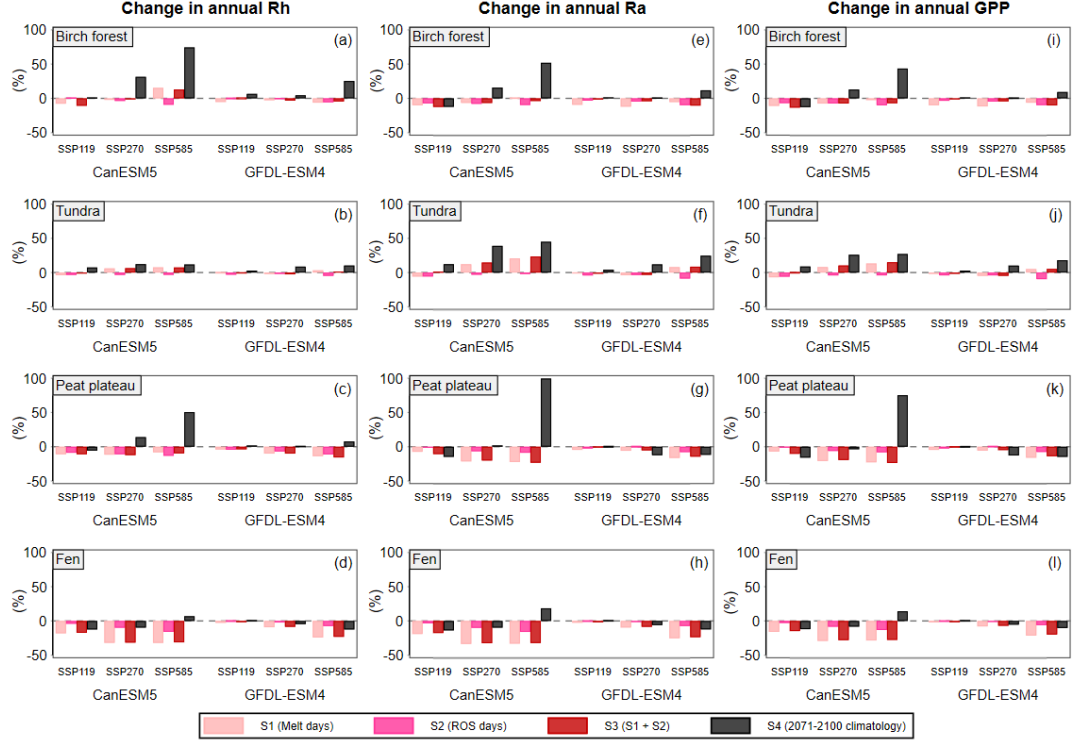
Increases in GT can stimulate microbial activity and accelerate litter and soil decomposition rates, resulting in increased  $R_h$  (Natali et al., 2019). Accordingly, winter  $R_h$  increased or decreased by <5% at the fen, and up to 25% at the tundra and peat plateau, following the GT responses (Figure G1). Contrastingly, in response to the CanESM5 SSP585 scenario at the birch forest site, despite the overall lower winter GT, winter  $R_h$  increased by up to >200%. This may be explained because the modeled winter  $R_h$  in the birch forest is very low (6 g C m<sup>-2</sup>, compared to >30 g C m<sup>-2</sup> at the other sites), and even small increases in  $R_h$  during WWEs can result in substantial relative increases in winter emissions. A recent synthesis of in situ observations across the Arctic indicates that winter  $R_h$  accounts for a substantial portion of the arctic’s annual C budget (Natali et al., 2019). Winter  $R_h$  alone currently offsets ~40% of the measured annual vegetation C uptake at our sites. Applying the winter  $R_h$  response curve to GT by Natali et al., (2019) (Q10 = 2.9), WWE-induced impacts on winter GT of the magnitudes reported here could change total winter  $R_h$  by up to 25%. Hence, realistically simulating the effects of WWEs on GT is important for improving estimates of GHG emissions in high latitudes.

The modelled CH<sub>4</sub> emissions at the peat plateau and fen sites decreased under all WWE experiments due to WWE-induced decreases in GT and GWC (Figure G2). At the fen site, emissions halved mostly due to lower water tables in the non-winter season.

Overall, the year-round ecosystem C exchange (i.e. NEE) of the birch forest, tundra, and peat plateau sites decreased (i.e., became a smaller C sink) considerably under most WWE experiments (Figure G3), generally between 20% and 50%, and up to 90% occasionally in the tundra site, due to larger reductions in vegetation C assimilation compared to the C losses from  $R_h$ . Contrastingly, NEE at the fen site increased weakly (i.e., became a stronger C sink), mostly due to large reductions in  $R_h$ . Noticeably, the changes in NEE caused by WWEs (S1-S3) are substantial and of similar magnitude to those caused by shifts in future winter climatologies (S4). This further indicates that WWEs, despite their short duration, may have the potential to induce changes in high-latitude ecosystem C cycling of magnitudes comparable to those induced by long-term climatic trends.

Given the observed discrepancies in modeled vs measured GT responses to

WWEs (section 3.2.1), the modeled impacts on ecosystems C fluxes reported here should not be interpreted as a direction prediction of future impacts of WWEs, but rather as a sensitivity test of the current model’s responses to altered levels of WWEs.



**Figure 2.** Differences between the MANIPULATION (S1-S4) and the HISTORICAL runs (S0), for annual Rh (%; left column), annual Ra (%; middle column), and annual GPP (%; right column), at each site.

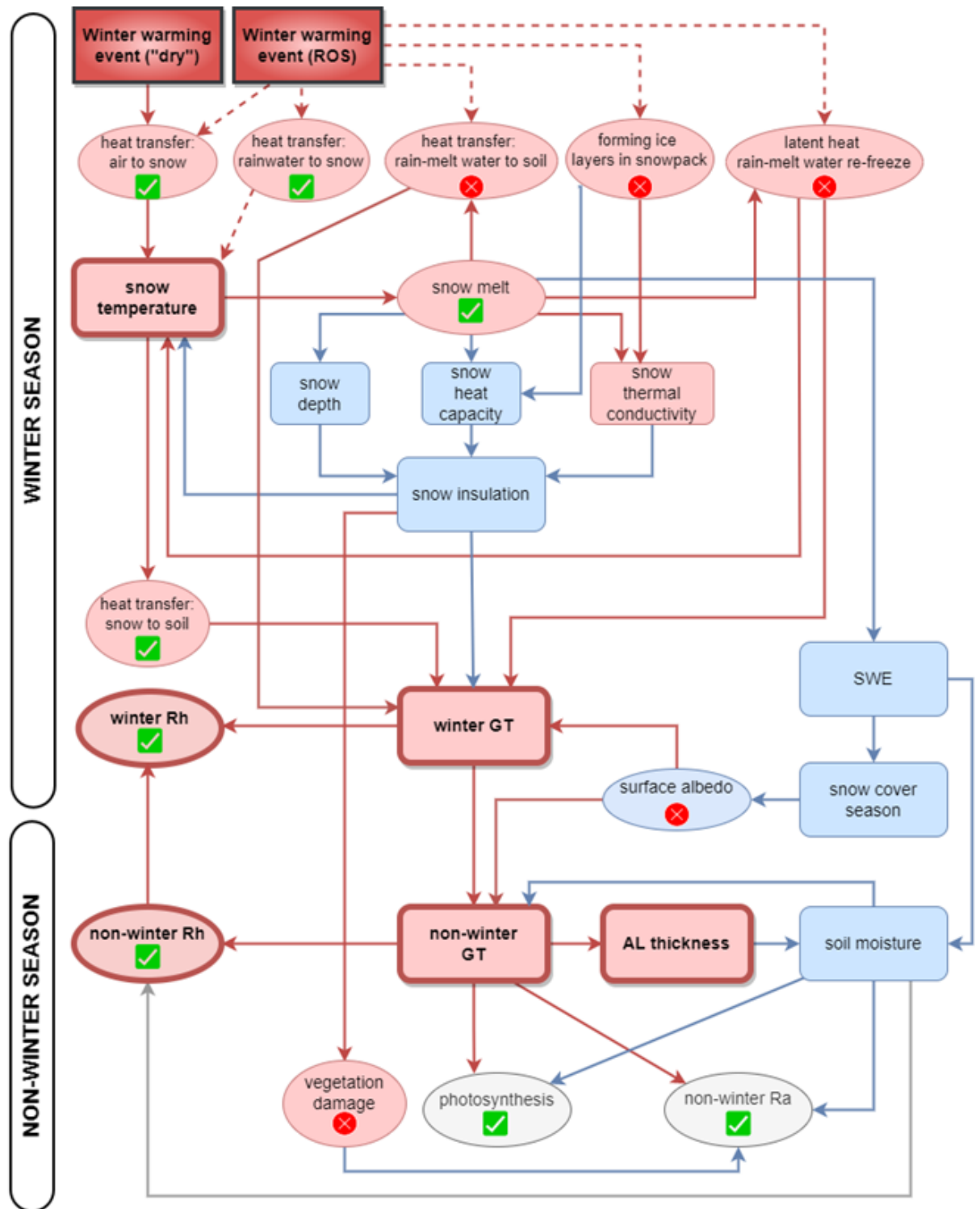
### 3.4.3 Model limitations and potential developments

LPJ-GUESS has difficulties in capturing the physical changes in snow depth induced by WWEs. We identified the lack of surface energy balance in LPJ-GUESS as one of the main limitations to simulating WWE impacts on GT. Heat transfer between air-snow-soil layers is simulated using the Crank-Nicholson finite difference scheme (Crank and Nicolson, 1996). This indirect method of defining heat transfer may significantly affect the computed snow layer and ground temperatures, and the rate and magnitude of snowmelt events. Additionally, the model’s daily timestep may be too coarse to capture the sub-daily freeze-thaw cycles and hydrological processes within the snowpack.

In the model, heat transfer is affected by the changes in snow layer temperature

and thermal properties, and the latent heat release upon freezing is not captured (Figure 3). The SA showed that the current model setup is not sensitive to changes in liquid water holding capacity in snow layers (Figure D1-3), potentially due to the simplistic water retention scheme applied. Rainfall infiltration follows a bucket model approach, limited by each snow layer’s maximum water-holding capacity. Precipitation from ROS events and melt water is quickly forwarded to the soil as runoff at the simulated time step (i.e., daily) when the maximum liquid holding capacity of a layer is reached. If the ground is frozen, the excess liquid water will not stay in the bottom snow layer, but drain out as surface runoff. This feature also prevents the formation of ice layers of high thermal conductivity within the snow layers, as many observational studies suggest (e.g., Langlois et al., 2017), which could influence the simulated GT. Observations suggest major ROS events may have durable impacts on GT (e.g. Westermann et al., 2011), but the current model setup cannot capture such persistent effects due to the simple water retention scheme and the lacking processes related to energy balance.

The LPJ-GUESS version used in this study has an intermediate complexity snow scheme, similar to many ecosystem models. These modules are developed and tuned to represent average conditions rather than capturing extreme and smaller-scale phenomena such as WWEs. There is a need for either further snow scheme development in LPJ-GUESS or evaluating a more complex, designated snow model to address the listed shortcomings and capture internal snow dynamics on a finer spatio-temporal scale. A recent extension of the model with detailed land surface processes and surface energy balance LPJ-GUESS LSMv1.0 (Belda et al., 2022) could be used in future studies to assess whether the model-measurements mismatch is reduced when using the LPJ-GUESS with detailed energy balance and sub-daily processes. This land surface model version of LPJ-GUESS needs to be thoroughly evaluated and tested in high latitude environments. Regional modelling studies are required to further understand how WWEs might affect the pan-Arctic carbon budget.



**Figure 3.** Theoretical model of the WWE impacts. Box colors indicate the overall direction of changes (red=increase, blue=decrease) in the variables based on the literature. Thick outlines and bold text indicate a disagreement between the literature and our simulations. Arrow colors show the direction of the change exerted by each process. Dashed lines refer to ROS-related processes. Grey boxes and lines refer to uncertain processes and responses. Green ticks and red crosses indicate WWE-related processes that are, or are not, implicitly implemented in the current model version.

## 5 Conclusions

We applied future-simulated WWE experiments in LPJ-GUESS to investigate the potential effects of these events on four dominant ecosystems in subarctic Sweden. The modeled impacts of WWEs on the ecosystem variables were substantial and of magnitudes often comparable to those of altered winter climatologies. These events induced reductions in GT which altered numerous biogeochemical processes and resulted in substantial changes in ecosystem CO<sub>2</sub> uptake. This highlights the need to realistically represent the effects of WWEs in ecosystem models -which are still largely overlooked especially in regional and large scale studies- to improve estimates of the current and future high-latitude C budget. The direction of the modeled impacts on GT differed from the majority of the observation-based literature. We identified the current model limitations contributing to this mismatch, including 1) the lack of surface energy balance, 2) the model's daily timestep, 3) and the simplistic water retention scheme applied in the LPJ-GUESS snow scheme.

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## Open Research

*The code version used for this study is stored in a central code repository and will be made accessible upon request.*

*We provided the necessary descriptions for transparency and traceability of the analysis using our community standards.*

Observational data used in this study can be retrieved from the following in-text data citation references: ANS (2020) [dataset, accessible upon request], SMHI (2020) [dataset accessible via <https://www.smhi.se/data/utforskarenoppna-data/?p=1&q=>], Sheffield et al., (2006) [dataset available at <http://hydrology.princeton.edu/>], Global Monitoring Laboratory [dataset available at <https://gml.noaa.gov/ccgg/trends/>], Batjes et al., (2012) [dataset available at [www.isric.org](http://www.isric.org)], Eyring et al., (2016) [dataset accessible at <https://esgf-data.dkrz.de/search/cmip6-dkrz/>], ICOS (2019) [datasets accessible at <https://hdl.handle.net/11676/0WzAlJlkSQDK2YuLXnkw6BX> and <https://hdl.handle.net/11676/jGBBiZrsgz19J47noGGPzpPf>], Jackowicz-Korczynski et al., (2010) [data included in the paper, <https://doi.org/10.1029/2008JG000913>].

Observational data from Heliasz (2012), Christensen et al. 2012, and Finderup Nielsen et al. (2019), and that listed in the Supplementary material as A. Michelsen, not published,

M. Johansson, not published, and D. Pascual, not published, will be available in a repository (<https://dataguru.lu.se/> or PANGAEA) by the time the article is accepted.

The output data is available in the supporting information, figures, and/or tables, during peer review, and will be deposited to (<https://dataguru.lu.se/> or PANGAEA) by the time the article is accepted.

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