Response to reviewer comment 1:

Specific comments

Pg1, L43: In addition to increased temperature, the projected increases in high latitude precipitation could also accelerate the release of permafrost carbon (e.g., Chang et al., 2019; Grant et al., 2017).

- We thank the reviewer for the suggested references. These new references will be added in the revised manuscript.

Pg1, L46-47: Can you give a quantitative description about the release of greenhouse gases (e.g., in terms of g CO_2-eq/m2)? How about Knoblauch et al. (2018) that found strong CH_4 production under anoxic conditions?

- We will add the following section in the revised manuscript version:

"However, for a future model estimate, Knoblauch et al (2018) predicts twice as much permafrost carbon release in anoxic conditions (241±138 g CO_2 kgC-1) compared to oxic conditions (113±58 g CO_2 kgC-1) by 2100.".

Pg2, L1-3: There are many other "detailed processes representations" that can alter high latitude CH_4 emissions in addition to surface wetland coverage. For example, the representations of permafrost thaw stage, surface topography, vegetation and microbial community compositions (e.g., Grant et al., 2017; Malhotra & Roulet, 2015; McCalley et al., 2014; Olefeldt et al., 2013).

- We thank the reviewer for these suggestions. We agree to include more detailed processes that influence the high latitude CH_4 emissions in the revised version. The following section will be added in the revised manuscript:

"Besides surface wetland conditions, models should also properly estimate permafrost thaw stage (Malhotra & Roulet, 2015), changing surface topography (Olefeldt et al., 2013), and surface vegetation and microbial conditions (Grant et al., 2017) in order to improve estimations of surface CH_4 emissions."

Pg7 Fig. 3: It might be a good idea to include the simulated soil temperature map here to (1) confirm it aligns reasonably with the simulated ground subsidence; (2) give a sense of how much warming leads to this amount of ground subsidence. Also, if the blue regions (subsidence<0.1m) are close to 0 degree C, wouldn't it suggest a potentially strong ground subsidence with the projected warming after 2010?

- We thank the reviewer for this suggestion and we want to emphasize that the scope of our current work is the connection between subsidence and surface water since the relation between subsidence and soil temperature/moisture was thoroughly discussed in the previous work: Lee et al. 2014. So for the sake of keeping the manuscript concise, we would like to refer to Lee et al. (2014) for the soil temperature diagnostics.

- The blue regions with subsidence <0.1m, the reviewer mention here, can indeed indicate a strong subsidence in the future where the soil temperatures are close to 0. We would like to emphasize that this is one of the motivations to use our new parameterization for future simulations and investigate the subsidence under warming scenarios.

Pg8, Fig.4: The spatially averaged sigma-micro between the two sets of runs are very similar. Can you include the variability along with the mean values? It appears that the model is extremely sensitive to a parameter (sigma-micro) that exhibits limited temporal variability. How do the author propose to find realistic sigma-micro values for contemporary and future simulations? Once the parameterization proposed in this study is applied to ESMs, it will trigger significant changes in surface hydrology and thereby biogeochemical feedbacks resulting from sigma-micro selection along (not including the parameterization uncertainty).

- We understand the reviewer's concern about the strength of microsigma parameter in our model. The variability of spatially averaged microsigma in Exice experiment is quite small indeed (variance: 2.8e-8, standard dev.:1.6e-4), so for the figure it doesn't make sense to add these in the manuscript. With the current knowledge, there is no perfect way to optimize the microsigma parameter for each gridbox in global simulations, this is why we tried to estimate micro-sigma by coupling to other well-known physical processes like excess ice melt. Since there is no global dataset to directly compare with our model results, one should be cautious interpreting our model's contemporary and future estimates. One avenue to constrain our parameterization will be to use the terrestrial greenhouse gas fluxes, once we use the biogeochemistry coupled to our parameterization, and this is for the next step in our work.

Response to reviewer comment 2:

General Comments

One of my main concerns with the parametrization pertains to the use of the accumulated subsidence for estimating the changes in microtopography. I see this as problematic as subsidence in the model can only increase over time (as the Lee scheme does not account for the formation of soil ice) and the authors introduce a fixed threshold above which further subsidence increases the microtopographic parameter rather than decreasing it. Hence, for the scheme to produce meaningful changes in inundated fraction, it does not only need to be initialized with the correct microtopography and soil ice content but also with reliable information of how much subsidence has happened in the past in any given grid box; in other words one would have to know, how close the subsidence is to passing the threshold when it will lead to an increase in sigma; and I am not aware of any dataset that could provide this information. In their study the authors avoid this initialization problem by starting the simulation with zero-subsidence and then having a 100-year spin-up period. But in this case, the results will be highly dependant on the selection of the spin up period, e.g. if the spin up of the model would have been done for 1000 instead of 100 years the results could look very different as in many grid-boxes the subsidence may have already passed the 0.5m-threshold meaning that the inundated fraction would actually decrease during the simulation.

- We acknowledge the reviewer's concern. We agree that this is one of the largest sources of uncertainty in our work. As the reviewer pointed out, our parameterization depends much on the initialization of excess ice and there is currently no global scale dataset to parameterize and evaluate the model. One feasible proxy for evaluating the surface inundation is to use the terrestrial CO_2 and CH_4 fluxes once we use our parameterization coupled to the CLM biogeochemistry module. This is the aim for the next step in our work and we hope that our work can motivate the observation community to collect such dataset.

- The spin up procedure was sufficiently long enough to bring the physical state into equilibrium, since we did not use the biogeochemistry, we did not need a longer spin up period than 100 years. Also the excess ice melt comes to an equilibrium with the spin up climate state so a longer spin up would not change the initial excess ice melt conditions.

Additionally, even though the authors make it clear that this is merely a first step, I am not fully convinced by the arguments that are being made in favour of the chosen parametrisations/assumptions. On pages 5 (l. 31) - 6 (l. 2) the authors claim that the simulated changes in inundated fraction stay within the range that results from halving or doubling the reference value of sigma; but I fail to see how that validates the coupling assumption? It merely shows that the parametrisation has a certain sensitivity, but how sensitive should it actually be?

- We have chosen to double and halve the reference microsigma value in the sensitivity analysis to show the upper and lower boundary of the sensitivity in fh2osfc with changing microsigma. The behavior of fh2osfc in these sensitivity simulations support that the dynamic parameterization in this study does not lead to unrealistic fh2osfc values in the simulations under present day climate. This test is merely to constrain any extreme sensitivity cases that might have originated from our conceptual scheme. Finding the best sensitivity of surface inundation to soil subsidence is beyond the scope of this study and currently very challenging to estimate with global observational datasets.

Also, while I can see a certain spatial correlation between the simulated subsidence and the changes in microtopography, i.e. Fig 3 and Fig 2a, I have a very hard time seeing any meaningful correlation between the changes in microtopgraphy (Fig. 2a) and changes in inundated fraction (Fig. 2b).

- The subsidence directly dictates the microsigma changes in the code, therefore, it is more straightforward to diagnose the relation between subsidence and microsigma than subsidence and fh2osfc. We agree with the reviewer that it is difficult to tease out direct relationship between microsigma changes and surface inundation. This is due to the fact that surface inundation is not only affected by the subsidence but also by combination of factors such as precipitation, air temperature, and soil moisture. Hence, the fh2osfc changes in Fig2b is difficult to interpret only from the changes in microtopography under excess ice melting. Yet, we would like to draw the reviewer's attention to the extreme subsidence areas (red points in Fig2a) and the corresponding changes (even though very small) in the surface inundation map (small blue areas inFig 2b), which suggests that our parameterization is creating surface inundation at the areas where it should. Figures 4 and 5 are added for similar reasons to compare the changes in fh2osfc in global and point scale dynamics. The future simulations under climate warming will show pronounced subsidence (Lee et al., 2014) and the consequent effects on surface inundation will be more visible.

But most importantly, I am not convinced by the comparison to the GIEMS dataset (page 9, l.6 - page 10, l.6). In Figure 6. there is almost no difference in the inundated fractions simulated with the two model versions. And if there was any difference I do not understand how that could demonstrate that it is beneficial to use the new scheme. The control simulation uses the present day sigma and should therefore also result in the best simulated present day inundated fractions. If the simulations with the new scheme give inundated fractions that are closer to the observations (which is not visible in the plots) it merely means that the function CLM uses to compute the inundated fraction could be improved, but not that the reference microtopography is wrong. So at best this comparison shows that the new scheme doesn't change the microtopography so much that it substantially affects the simulated present day inundated fraction. As the scheme is used to capture the dynamics related to subsidence, it would be key to show a comparison with observed trends/changes in the inundated fraction, in order to demonstrate that the scheme performs well.

- We thank the reviewer for opening this point to discussion. Fig. 6 indeed does not show a large difference between the Control and Exice simulations. However, as we pointed out in the discussion, we intended to show that our new parameterization does not create unrealistic values compared to the Control simulation and this work is merely to increase our confidence to use the new dynamic parameterization for future climate change scenarios, where the differences due to major subsidence will be more pronounced. So, we do not claim the current CLM microsigma parameter is faulty, our new parameterization introduces a temporal variability to the microsigma parameter and it shouldn't diverge too much with the present day conditions. Hence, the similarity between Control and Exice simulations in Fig 6 supports our aim. On the other hand, we use the GIEMS dataset to additionally show that the regions where extensive high surface inundation occurs in observational dataset and to confirm that the model results correspond well with the observations in the spatial patterns of surface inundation. Since the GIEMS dataset was not a very long time series, we couldn't use this dataset for direct comparison over time. However, Fig 5 demonstrates model's behaviour in time for different climatic conditions and the deviations from the control run are quite distinguishable.

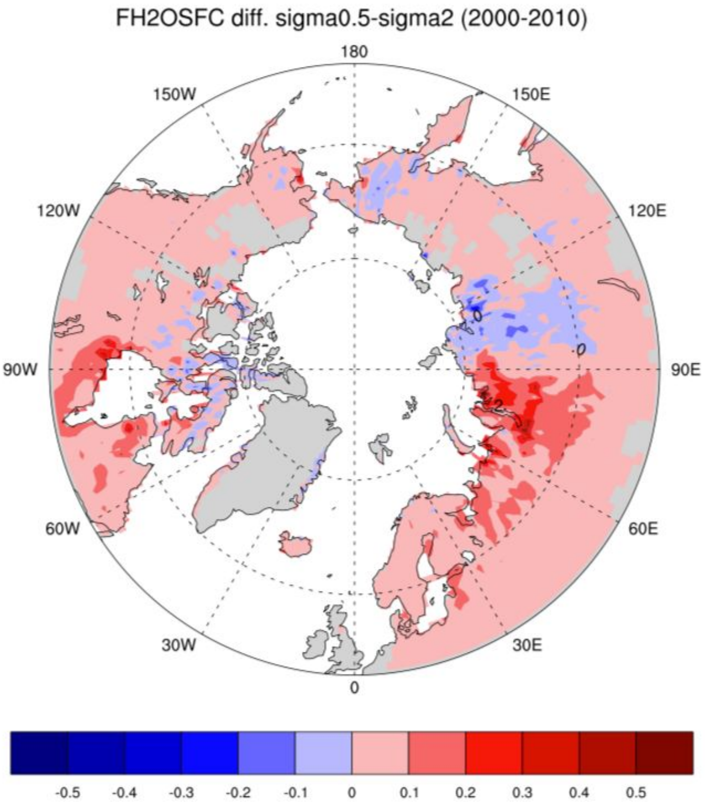
Consequently, until the authors demonstrate the scheme's ability to improve the models surface water dynamics and provide a strategy for the initialization and spinup of the model, I can not agree with the their conclusion that "the parametrization is implemented successfully and can be used for further climate scenarios".

- We believe we have answered some of the reviewer's concerns and we are not sure if the reviewer has some other suggestions at this point. We want to clarify that one of the points of this manuscript is to show a new parameterization that works globally for a land surface scheme. We suggest to revise our conclusion points to tone down the implications of this study that it is the first step in this kind of parameterization. But more importantly, this study really brings out the importance of observational data and we encourage observations to take this into account.

Specific Comments

- p.2, l.24-l.27: As the subsidence simulated by the scheme is a key input to your model it would be very helpful if you could provide some more details on the scheme by Lee et al..
- we are adding some details of Lee et al. scheme in the methods section in the revised manuscript.
- P.3, l.32: Why preliminary?
- wrong choice of word, changed 'preliminary' to 'conceptual'
- P.3, l.35: Here, it would be very helpful if you could clarify whether s is indeed the accumulated subsidence since the beginning of the simulation.
- yes we added clarification in the text
- P.4, l.12ff: Is there a specific reason why you do the spinup using the forcing from 1901-1930 while you start your simulation in the year 1860? Wouldn't it make more sense to use the climate forcing from the beginning?.
- it was just a standard procedure for CLM to use the 1901-1930 block for the spinup and we wanted to stay consistent.
- P.4, l.18ff: Could you also indicate how the microtopography was initialized in the Exice experiments. I just assumed you use the same index that is used for the control simulation (Fig. S1).

- yes it was using the same reference microsigma. This information is now added in the text
- Fig. 1: I find it quite difficult to judge the differences in fh2osfc between the simulations. Maybe you could show the differences between sigma-0.5 and sigma-2 as a sub-figure? Or maybe you could also provide a graph with sigma and d on the x and y axes and fh2osfc as a colour to give a more systematic overview?
- we are adding the difference map sigma-0.5 - sigma-2 in the supplements



- P.6, l.1f: I fail to see how this supports your coupling assumption. It merely says something about the sensitivity of your parametrization. Without knowing which sensitivity should be expected it is very hard to use this in support for the assumption.
- discussed this above in the main points
- Fig. 2: I was quite surprised to see so little spatial correlation between the change in microtopography and the change in inundated fraction (could you maybe calculate a correlation coefficient). While sigma is almost exclusively lower in Exise, there is actually quite a number places where the inundated fraction is also smaller. Additionally, most of the areas in which you find the strongest changes in microtopography show now substantial increase in the inundated fraction. Thus I would not say that the patterns are similar. Here I think more information, especially on the changes in the surface water level, is required for the reader to better understand the plots.
- this point is also discussed above in the main points
- P.6, l.8-l.13f: I find this formulation problematic. The connection between melting ground ice and surface hydrology is not suggested by the correlations between Figs2 and 3, but because the connections where directly implemented with Lee et al.'s and your scheme. But, while I do see a correlation between Figs 2a and 3, I do not see the same patterns in Fig 2b.

- this point is also discussed above in the main points
- P.7, l.7ff: If you initialize your simulation with the present day sigma and the present day ice content, and then run it for 240 years (spinup + 1860 - 2000) during which time the ice content can only decrease, wouldn't you necessary end up with a worse microtopography for present day?. I presume that the initialisation/ spinup procedure was carried out because there is no data to consistently initialize the model either at 1860 or at present day? But what would be the strategy to initialize/ spin up the model for future simulations?
- yes it is true that the microtopography is expected to be different in accordance to the subsidence levels occurred during the spin up and transient simulation, but the idea here is to constrain the dynamic parameterization and to avoid any major extreme sensitivity from the conceptual method. since there is no way to properly initialize the soil subsidence, we will use other biogeochemical variables (co2/ch4 fluxes) to constrain the surface inundation in our future work, but it is out of scope of this merely model development manuscript.
- Fig. 4 and Fig 5.: Why is the difference in fh2osfc so variable even if there are no pronounced changes in sigma and the two experiments use the same forcing?.
- In the CLM, fh2osfc is also affected by soil and atmospheric changes, however, Fig 5 shows that the changes in microsigma influence fh2osfc on a point scale. This change is difficult to point out in larger spatial scale as in Fig 4, where the spatial averages are used.

Response to reviewer comment 3:

Special comments

p.3 l.1: Cound you explain the effect of the modified parameters (e.g. microtpography distribution and surface inundated fraction) on the entire model? Those descriotions would be helpful to understand the proposed parameterization is crucial to assess the biogeochemical feedbacks.

- We thank the reviewer for this suggestion and the following text will be added to the revised manuscript:

"Surface water is defined by spatial scale elevation variations that is the microtopography. The microtopography is normally distributed around the grid cell mean elevation. The fractional area of the grid cell that is inundated (fh2osfc) can be calculated with the standard deviation of this microtopographic distribution. The surface inundated fraction, in turn, affects the soil heat/water/carbon fluxes with the atmosphere."

p.3 l.24-33: The delineation of the actual relathinship between ground subsidence and microtopography is necessary to understand the relevance of modeling instead of a required parameterization by governing equations in CLM.

- We are not sure if the reviewer is requesting us to show the relationship between ground subsidence and microtopography in reality, which is hard to assess due to the lack of observational data. As a result, we used existing parameterization in the CLM surface hydrology based on TOP model. We acknowledge that this is only the first step in this kind of parameterization and hope that our study can bring attention to observational community for such observational data.

p.3 l.35: Related to the previous comment, if you could calculate more realistic value of microsigma with finer-resolution topographic data and subsidence information, does it improve the model applicability? It would be helpful if you explain the limitation of "modeling (conceptulization)" and "parameterization" respectively.

- The parameterization in models such as CLM should focus more on functionality and that this is a very conceptual step in the parameterization. Next step will be subgrid-scale representation of this process but this is not within the scope of our study. We refer to Aas et al. (2019) for the subgrid scale process representation in the revised manuscript.

p.10 fig.6: As the authors pointed out, it is difficult to directly compare inundated area between GIEMS dataset and simulated results due to the gap of definitions of water surface. However, I think some other variables relating water budget (e.g. river discharge) are modified by the proposed parameterization and can be compared with observation data. I apologize if I misunderstand the numerical implementation in CLM.

- We thank the reviewer for the question. It is correct that other water budget variables are affected from our parameterization, however for river discharge, the direct effects from the surface subsidence are minor compared to permafrost thaw related spring river discharge increases, hence not useful to validate the new model.

References:

Aas, Kjetil S., et al. "Thaw processes in ice-rich permafrost landscapes represented with laterally coupled tiles in a land surface model." *The Cryosphere* 13.2 (2019): 591-609.

Response to reviewer comment 4:

Major issues

1. The assumption for the proposed equation may not be correct. The authors assumed that decreased micro topography distribution (microsigma) represents increased surface inundation (fh2osfc). However, from equation 1, it seems that the assumption is true only when surface water level d is greater than 0, hence fh2osfc is greater than 0.5.

- We are not sure if the reviewer is asking about negative water level conditions, but the model does not allow negative surface water levels (d), so the Eq. 1 does indeed show an inverse relation between microsigma and fh2osfc. We hope this clarifies the reviewer's concern.

2. When the subsidence value surpasses the 0.5 m threshold, microsigma suddenly increases as shown in the lower middle panel of figure 5. Does this sudden change represent any physical processes?

- Yes it does actually. The increase in microsigma represents the extreme cases where soil subsidence leads to drying of the surface (Liljedahl et al. 2016), which is explained in the text (P3: last paragraph, P6: last paragraph).

3. Is there any feedback from surface water fraction to other hydrology variables (e.g. soil moisture) in the model?

- The surface water fraction does affect the evapotranspiration and soil moisture but the effects are small when compared to other factors such as precipitation and permafrost thaw. So, yes, there are feedbacks between surface water fraction and other hydrological variables, but not big enough compared to our new parameterization.

4. The initial conditions seem to be important for the simulations. How was the spin up period determined? Is 100-years enough for spin up?

- The spinup period of 100 years is chosen to make sure the soil physical variables (soil temperature/moisture) are equilibrated. And it was long enough to avoid any big drifts in these variables. However, for the soil subsidence it is hard to determine an optimum spin up period since the contemporary or past soil excess ice data is very uncertain and hard to constrain the initial conditions. However, the soil excess ice melt also stabilizes with the spin up climate so the spin up period was long enough to have an initial condition for our simulations.

5. There are not enough validations performed. It is not clear for me which simulation is better when comparing with the observation. Is it possible to validate time series of surface water fraction using GIEMS dataset?

- Unfortunately it was not possible to use GIEMS dataset to compare the temporal dynamics, since the dataset period was too short to see any major differences. Also as discussed in response to other reviewers' comments, this paper merely aims to show that the new parameterization is in line with the current model and does not create extreme conditions. We did not expect big changes compared to the Control simulation, but we do plan to use this for future climate warming scenarios, where higher subsidence levels (Lee et al., 2014) will certainly create more distinguished results to Control simulation.

Minor issues

P1 L28-31: Is this true? The authors say "The largest increases in fh2osfc are observed in central Siberia and southeastern Russia" on line 27 of page 6.

- The text in abstract is about the general increases in fh2osfc, whereas the text in P6:L27 is related to the difference between Exice and Control simulations and more about the direct effects of dynamic parameterization. In the end, Fig6 shows that the higher inundated fractions are actually around western Siberia and around the Hudson Bay.

P3 Equation 2: What is eta?

- "eta" here is just an adjustable parameter.

P5 L11-15: This is confusing. sigma_micro is defined as microtopography distribution on line 9 of page 3. Why does lower sigma_micro represent increased variability in surface microtopography?

- This is related to the distribution of surface microtopography. There is increased variability on surface of gridbox but the distribution of different levels is lowered, hence a lower microsigma.

P8 L10: "higher microsigma" should be "lower microsigma"?

- We thank the reviewer for the correction, the mistake is corrected now.

Ground subsidence effects on simulating dynamic high latitude surface inundation under permafrost thaw using CLM5

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Abstract

Simulating surface inundation is particularly challenging for the high latitude permafrost regions. Ice-rich permafrost thaw can create expanding thermokarst lakes as well as shrinking large wetlands. Such processes can have major biogeochemical implications and feedbacks to the climate system by altering the pathways and rates of permafrost carbon release. However, the processes associated with it have not yet been properly represented in Earth system models. We show a new model parameterization that allows direct representation of surface water dynamics in CLM (Community Land Model), the land surface model of several Earth System Models. Specifically, we coupled permafrost-thaw induced ground subsidence and surface microtopography distribution to represent surface water dynamics in the high latitudes. Our results show increased surface water fractions around western Siberian plains and northeastern territories of Canada. Additionally, localized drainage events correspond well to severe ground subsidence events. Our parameterization is one of the first steps towards a process-oriented representation of surface hydrology, which is crucial to assess the biogeochemical feedbacks between land and the atmosphere under changing climate.

1. Introduction

Northern high latitudes experience pronounced warming due to Arctic amplification (Serreze and Francis, 2006). Within the last decades, temperature increase in the Arctic has been twice the amount of that in the tropics (Solomon et al., 2007). The abrupt increase in Arctic temperatures threatens to destabilize the global permafrost areas and can alter land surface structures, which can lead to releasing considerable amounts of permafrost carbon as greenhouse gases to the climate system (Schuur et al., 2008). Similarly, increased precipitation can accelerate the release of permafrost carbon in high latitudes (Chang et al., 2019; Grant et al., 2017). The balance between CO_2 and CH_4 release from permafrost depends largely on the organic matter decomposition pathway; larger inundated areas release more CH_4 than CO_2 using the anaerobic pathway but overall release of greenhouse gases is greater under aerobic conditions (Lee et al. 2014; Treat et al. 2015). However, for a future model estimate, Knoblauch et al (2018) predicts twice as much permafrost carbon release in anoxic conditions (241±138 g CO2 kgC-1) compared to oxic conditions (113±58 g CO2 kgC-1) by 2100. The main natural sources of CH_4 emissions are from tropical wetlands, however the contributions from high latitude wetlands are increasing each decade (Saunois et al., 2016) with further thawing of permafrost.

With high percentage of surface wetland coverage (Grosse et al., 2013; Muster et al., 2017), characterizing high latitude CH_4 emissions require detailed process representations in models. Besides surface wetland conditions, models should also properly estimate permafrost thaw stage (Malhotra & Roulet, 2015), changing surface topography (Olefeldt et al., 2013), and surface vegetation and microbial conditions (Grant et al., 2017) in order to improve estimations of surface CH4 emissions.
However, Earth system models (ESMs) used in the future climate projections struggle to represent the complex physical/hydrological changes in the permafrost covered high latitude regions. Therefore, it is necessary to improve model representation of surface hydrology processes within the ESMs.

Permafrost processes have now been represented commonly within the land surface models (Lawrence et al., 2008; Gouttevin et al., 2012; Ekici et al., 2014; Chadburn et al., 2015), however, the complex hydrological feedbacks between degrading permafrost and thermokarst lake formations have been a major challenge. An extensive review of wetland modeling activities and an intercomparison effort of evaluating methane-modeling approaches are given in Wania et al. (2013) and Melton et al. (2013). These studies, however, do not include permafrost specific features such as excess ice in frozen soils, therefore they have tendency to under-represent key processes associated to permafrost thaw. Excess ice melt within the frozen soils can lead to abrupt changes in the surface topography, creating subsided ground levels, which can enhance pond formation often recognized as thermokarst formation. Such changes in surface microtopography can be very effective in altering the soil thermal and hydrological conditions (Zona et al., 2011).

Lee et al. (2014) implemented surface subsidence processes in the Community Land Model (CLM: Oleson et al., 2013; Lawrence et al., 2011; Swenson et al., 2012) to overcome some of the limitations in representing processes associated with permafrost thaw and subsequent land surface subsidence. The surface conditions altered by the subsidence events change the microtopography of the area, which can further modify the surface hydrological conditions in reality. Lee et al. (2014) did not further couple the land surface subsidence with hydrological processes to represent subsequent changes in local hydrology created under permafrost thawing. Here we developed a conceptual coupling of excess ice melting and subsequent land surface subsidence with hydrology and show how implementing permafrost thaw induced subsidence affects surface microtopography distribution and surface inundation in the CLM model.

2. Methods

Simulating the effects of permafrost thaw on surface water dynamics requires a complex interaction of thermodynamics and hydrology within the model. Here we use the 1° spatial resolution simulations of CLM5 (Lawrence et al., submitted 2018) to represent such dynamics. CLM is a complex, process based terrestrial ecosystem model simulating biogeophysical and biogeochemical processes within the soil and vegetation level. Lee et al. (2014) have presented the excess ice implementation into CLM. The ground excess ice data from International Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997) are used to create an initial soil ice dataset to be prescribed into the model. This excess ice is added between 0.8 and 3.8 meters in CLM soil scheme where permafrost exists and increases the relevant soil layer thicknesses. The amount of excess ice for each gridcell is estimated by multiplying percent permafrost area with amount of excess ice from the Brown et al. (1997) dataset. The soil physical parameters (heat capacity and conductivity) are updated with the addition of excess ice. The excess ice in the model undergoes physical phase change but most importantly melting ice allows a first-order estimation of land surface subsidence under permafrost thaw. First the soil ice is allowed to melt and then the excess ice is subjected to phase change. Ice melt water is then added the soil hydrology scheme in CLM and can be directed as runoff if it exceeds saturation. The soil layer thicknesses are then updated with the disappearing amount of excess ice. Lee et al. (2014)'s scheme does not allow formation of excess ice after initialization.

In CLM, surface inundated fraction (fh2osfc) of each grid cell is calculated by using the microtopography distribution (σ_{micro}) and the surface water level (d) of the grid cell (Eq. 1 - 3). Surface water is defined by a spatial scale elevation variation that is the microtopography. The microtopography is normally distributed around the grid cell mean elevation. The fractional area of the grid cell that is inundated (f_{h2osfc}) can be calculated with the standard deviation of this microtopographic distribution. The surface inundated fraction, in turn, affects the soil heat/water/carbon fluxes with the atmosphere.

$$f_{h2osfc} = \frac{1}{2}\left(1 + erf\left(\frac{d}{\sigma_{micro}\sqrt{2}}\right)\right)$$

Eq.1: Parameterization of surface inundated fraction 'f_{h2osfc}' using an error function of surface water level 'd' (height in m relative to the gridcell mean elevation) and microtopography distribution 'σ_{micro}' (m).

$$\sigma_{micro} = \left(\beta + \beta_0\right)^{\eta}$$

Eq. 2: Microtopography distribution 'σ_{micro}' as a function of slope, where β is the prescribed topographic slope and "η" is an adjustable parameter.

$$\beta_0 = \left(\sigma_{\max}\right)^{\frac{1}{\eta}}$$

Eq. 3: Adjustable coefficient β_0 as a function of maximum topographical distribution 'σ_{max}'. Original value for σ_{max} is 0.4 while η is -3.

This parameterization is similar to the TOPMODEL approach (Beven and Kirkby, 1979), where a hypsometric function is used to define the height of standing water (*d*) within the gridbox by assuming a normal statistical distribution of ground level microtopography. In this study, the subsidence levels from permafrost thaw induced excess ice melt are coupled with σ_{micro} in order to represent the naturally occurring subsided landscapes within the permafrost-affected areas. With increasing excess ice melt, more subsidence occurs and the amount of subsidence redefines the surface σ_{micro}, which is inversely related to f_{h2osfc} (Eq. 1). Therefore, to represent increased f_{h2osfc}, σ_{micro} has to be decreased in value. However, σ_{micro} is the statistical distribution of surface microtopography, hence cannot be directly related to physical subsidence levels. Therefore, a conceptual method of relating σ_{micro} to an order of magnitude lower ground subsidence levels is used (Eq. 4). This first step of conceptualization can be improved with subgrid scale parameterization (Aas et al., 2019) in future studies.

$$\sigma'_{micro} = \begin{cases} \sigma_{micro} - s \div b, s < 0.5 \\ \sigma_{micro} + s \div b, s \geq 0.5 \end{cases}$$

Eq. 4: New microsigma parameterization 'σ'_{micro}' where '*s*' is the accumulated subsidence in meters and '*b*' is the adjustable parameter set to 10.

We implemented a conditional formulation regarding the severity of subsidence. In general, the surface is forced to allow more ponding of water with moderate levels of subsidence. However, advance levels of excess ice melt can degrade the surface levels so much that the small troughs created from the initial degradation can connect to create a drainage system that the grid box can no longer support any ponding (Liljedahl et al., 2016). For this reason, the excess ice melt has a reversed effect on σ_{micro} after a threshold value of 0.5 m (Eq.4). Choice of this threshold value is discussed in the following section.

We performed several experiments using CLM5 to assess the general response of surface hydrology to changing microsigma parameter values. First, the dependence of f_{h2osfc} to σ_{micro} is investigated by doubling σ_{micro} (experiment: Sigma-2) and reducing it by half (experiment: Sigma-0.5). Afterwards, initialized with the default microsigma distribution (Fig. S1), results of the new σ_{micro} parameterization (experiment: Exice) is compared to the default model version (experiment: Control), where subsidence does not alter σ_{micro} or f_{h2osfc} and to a satellite driven data product (GIEMS, the Global Inundation Extent from Multiple Satellites, Prigent et al., 2012). All experiments include 155-year transient simulations following a spin up procedure of repeating 1901-1930 climate forcing for 100 years. The transient 155-year simulation represents the time period from 1860 till 2015. CRU-NCEP (Viovy, 2009), a combined dataset of Climate Research Unit (CRU) and National Center for Environmental Protection (NCEP) reanalysis datasets, is used as the atmospheric forcing for these experiments.

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The GIEMS surface inundation dataset from Prigent et al. (2007, 2012) is used to compare the simulated inundated fractions. GIEMS uses a combination of satellite observations to derive the distribution and dynamics of the global surface water extent. The inundated areas are calculated using passive microwave observations from Special Sensor Microwave/Imager (SSM/I), active microwave observations from the scatterometer on board the European Remote Sensing (ERS) satellite and the normalized difference vegetation index (NDVI) from the Advanced Very High resolution Radiometer (AVHRR). The dataset provides monthly-mean values of surface water area from 1993 to 2007, with a spatial resolution of 0.25°. The dataset is spatially projected onto a 1° resolution grid for comparison with the model results.

3. Results and Discussion

In our experiments, surface inundation (f_{h2osfc}) increases where surface microtopography distribution (σ_{micro}) decreases (Fig. 1) as expected from the CLM parameterization. When σ_{micro} decreases (Sigma-0.5) compared to the original value (shown in Supplementary Figure S1), it results in very high f_{h2osfc} over western Siberia and Hudson Bay area, while increasing σ_{micro} (Sigma-2) results in lower f_{h2osfc} in general. In the original CLM parameterization, f_{h2osfc} is calculated with a static microtopography index (Fig. S1) derived from a prescribed topographic slope dataset (Oleson et al., 2013).

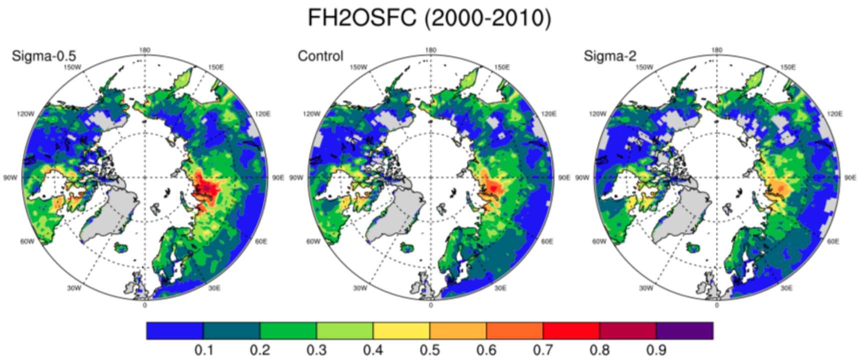

Fig. 1: High latitude (>50°N) maps of simulated surface water fractions (f_{h2osfc}) from Control, Sigma-0.5, and Sigma-2.0 experiments with different microsigma distributions averaged for the period 2000-2010.

Our results illustrate the dependence of f_{h2osfc} on σ_{micro} and how certain range of σ_{micro} values can result in very high f_{h2osfc}, and differences in f_{h2osfc} can be quite regional (Fig. S2). This relation emphasize the need for a dynamic circum-Arctic σ_{micro} value to capture the natural variability of surface conditions when representing permafrost thaw associated hydrological changes. In the Exice experiment, coupling excess ice melt induced ground subsidence to σ_{micro} leads to significant changes in surface hydrology (Fig. 2). In our simulations, σ_{micro} is consistently lower in Exice compared to Control at the end of the 20th century (Fig. 2a). This is the model representation of increased variability in surface microtopography due to uneven subsidence events within the gridcell. Particularly larger inundated fractions are simulated around western Siberia and northeast Canada, which conform well to the observational datasets of peatland

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distribution (Tarnocai et al., 2007; 2009). Several other observational estimates agree on the spatial distribution of high latitude peatlands, where most of the wetland formations are expected in the future (Melton et al., 2013). Therefore, the new parameterization of surface inundated fraction is a stepping-stone towards a more realistic representation of surface hydrology in permafrost-affected areas. Other modeling studies support these results with similar spatial patterns of surface wetland distributions (Wania et al., 2013; Melton et al., 2013). In the previous version of CLM, simulated inundated area shows slightly different patterns (Riley et al., 2011), mainly due to non-process based description of inundated fractions. We emphasize that although our parameterization is only conceptual, this is the first attempt towards coupling permafrost thaw associated land surface subsidence with hydrological changes in a land surface model within an ESM.

By introducing the effects of ground subsidence on σ_{micro}, a dynamic inundated fraction is calculated. However, there is no observed dataset to evaluate the relation between subsidence and ground topography, therefore an assumption had to be made regarding this coupling. In this study, changes in σ_{micro} are proportional to the changes in ground subsidence with the difference in an order of magnitude. This assumption is put to test by doubling and halving the initial σ_{micro} values and the results show 10 to 20 % change in surface inundated fractions (Fig. 1). The difference in dynamic parameterization (Fig. 2b) stays in between these values and on average shows a 10 – 15 % increase, thus supporting the coupling assumption.

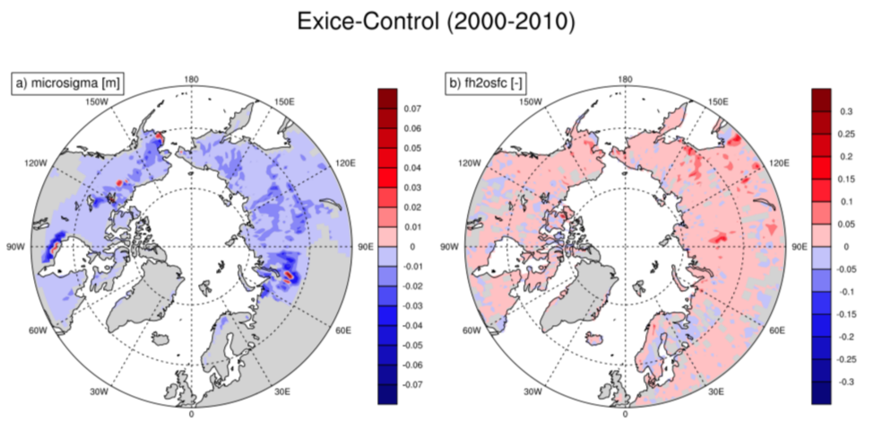

Fig. 2: Effects of coupled subsidence-microsigma parameterization on 'σ_{micro}' and 'f_{h2osfc}' from >50°N difference maps of Exice-Control experiments for the period 2000-2010.

As expected, the f_{h2osfc} and σ_{micro} changes are related to the ground subsidence processes in most cases. Exice experiment produces land surface subsidence in some gridcells (Fig. 3) similar to the spatial patterns exhibited in σ_{micro} and f_{h2osfc} in Fig. 2, suggesting that melting of excess ice affects changes in surface hydrology. This is most pronounced around western Siberia, south of Hudson Bay and around northwestern Canada and central Alaska, where initial excess ice was large (Lee et al. 2014). Simulated ground subsidence is associated to changes in surface inundated fraction (f_{h2osfc}) described in Fig. 2.

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As a result of subsidence threshold parameterization (see Methods), reversed effect of excess ice melting is shown in the σ_{micro} plots (Fig. 2a), where red points are directly related to the severe ground subsidence locations (Fig. 3). These areas consistently exhibit abrupt melting of excess ice leading to increased σ_{micro}. Larger negative deviations of σ_{micro} from the original values were observed in central Alaska, northwestern Canada, south of Hudson Bay, southwest Russia, central Siberia, and northern Yakutia regions of Russia (areas with dark blue in Fig2a). In reality, different landscapes should have a different threshold value, yet our work is aimed to capture the overall changes and general patterns rather than local conditions, so a preliminary choice of a single threshold value is used. Same areas show increased f_{h2osfc} compared to Control (Fig. 2b). The largest increases in f_{h2osfc} are observed in central Siberia and southeastern Russia, while some minor decreases in f_{h2osfc} values are present in an unevenly distributed pattern. It is important to add that the choice of 0.5 m threshold is arbitrary and can be modified according to the surface dataset of excess ice.

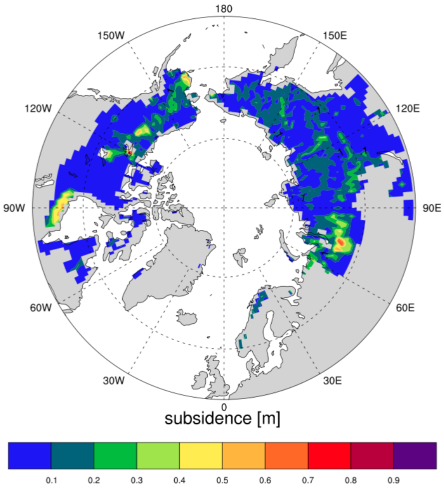

Fig. 3: High latitude (>50°N) map of ground subsidence simulated from the Exice experiment averaged for the period 2000-2010.

Spatially averaged timeseries of σ_{micro} and f_{h2osfc} show that in the Exice experiment σ_{micro} decreases over time and f_{h2osfc} shows a more dynamic change during the simulation (Fig. 4). The discrepancy in σ_{micro} between Exice and Control in the beginning of the simulation is due to prior excess ice melting during the spin-up period (Fig. S3) and the values continue to decrease throughout the 20^{th} century, while the decrease halts temporarily during 1960-1990 (microsigma-diff plot in Fig. 4). Higher f_{h2osfc} are observed in Exice experiment, however, the differences between Exice and Control show a general increase throughout the simulation except the period between 1960-1990. The spatially averaged f_{h2osfc} values exhibit a non-linear progression during the 20^{th} century (Fig. 4). Mainly the change in climate forcing contributes to this trend. Analyzing the CRUNCEP atmospheric forcing data suggests that the precipitation pattern over the experiment domain shows a sudden reduction at the beginning of 1960s (Fig. S4). Even though the average precipitation starts increasing again,

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the lower values contribute to the reduced f_{h2osfc} values. Similar changes occur with the patterns in atmospheric temperatures (Fig. S4), which is a direct forcing for permafrost thaw and ground subsidence. A process-based representation of f_{h2osfc} allows the model to naturally represent the temporal changes in climate. Hence, our representation of f_{h2osfc} will improve the estimation of future surface hydrological states under changing climatic conditions.

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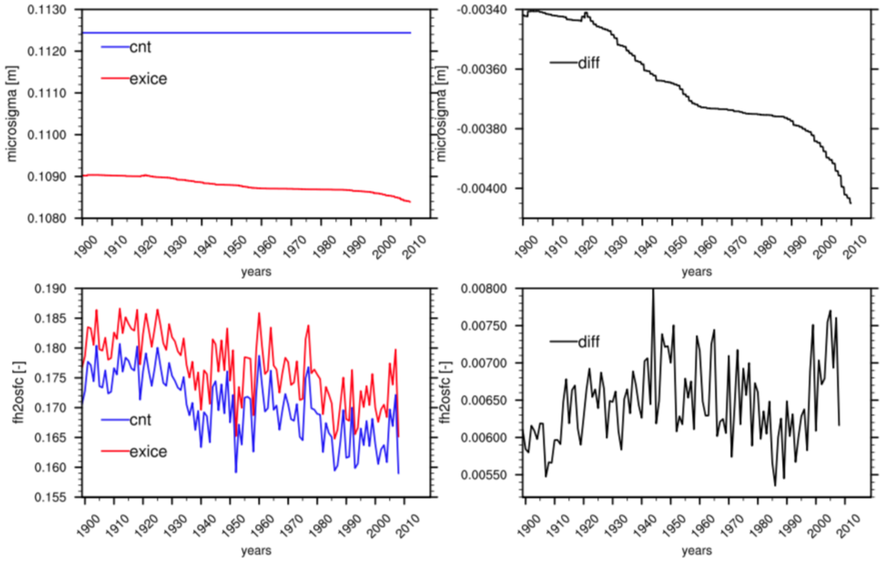

Fig. 4: Timeseries of spatially averaged high latitude (>50°N) σ_{micro} and annual maximum f_{h2osfc} variables from Exice and Control experiments together with the timeseries of Exice-Control difference (diff) for the period 1900-2010.

The direct effects of the new model parameterization are better analyzed while inspecting point scale changes as shown in Fig. 5. The three selected points show a range of scenarios to observe the effects of subsidence on microsigma and f_{h2osfc}. Point 1 has no change in subsidence during the simulation and with lower microsigma values in Exice (due to prior subsidence in spinup), the difference in f_{h2osfc} compared to Control simulation is always positive, meaning higher surface inundated fractions. In Point 2, Exice microsigma decreases due to the increase in subsidence during the simulation. These gradual changes are reflected in f_{h2osfc}, where sudden increases are shown around 1935 and 1955, exactly when the subsidence changes occur. Similarly in Point 3, subsidence causes a lower microsigma in the beginning of the simulation; however the subsidence values surpass the 0.5m threshold around 1920s, which causes the reversed effect on microsigma by increasing it compared to the Control experiment. Severe subsidence causing more drainage is represented in this way within our parameterization. The f_{h2osfc} values show this drainage with a sudden decrease at 1920 and continuing with mostly negative values throughout the simulation. These scenarios support the validity of our new parameterization that can be used for any future climate scenario for a better representation of surface hydrology and subsidence coupling.

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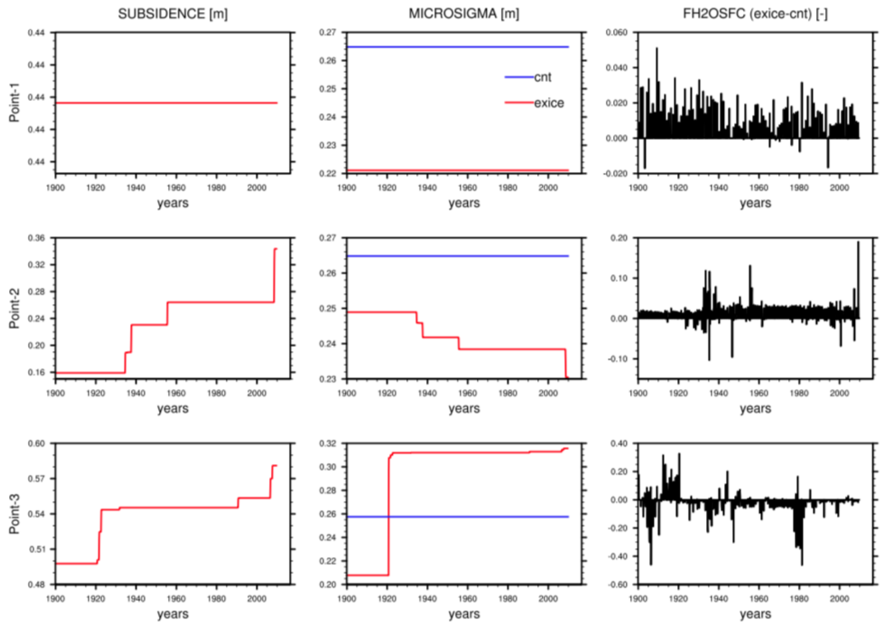

Fig. 5: Timeseries of subsidence, σ_{micro}, and f_{h2osfc} variables from Exice and Control experiments at three selected sites. Point 1: lat 54 N lon 272 E, Point 2: lat 64 N lon 80 E, Point 3: lat 65 N lon 70 E.

GIEMS dataset (Prigent et al., 2012) provides the surface area of wetlands for each gridbox. Fraction of wetland-covered gridbox is calculated to compare with the model results (Fig. 6). The range of estimated surface wetland fraction is different in the satellite dataset and model outputs; however, spatial distribution of surface inundated area is fairly comparable between the model and the satellite dataset. They both exhibit larger inundated fractions in western Siberia and around Hudson Bay. The ranges of estimated surface wetland fraction between the satellite dataset and model outputs are different due to differences in the definitions of inundated areas. However, spatial distribution of surface inundated area is comparable between the model and the satellite dataset, where both exhibit larger inundated fractions in western Siberia and Hudson Bay. Since our model provides the fraction of gridbox that is inundated, the satellite dataset had to be converted from actual wetland area to fractions. The GIEMS dataset assumes 773 km^2 gridboxes all over the globe (Prigent et al., 2007), which creates grid-size problems comparing to model gridbox area. Another issue with such comparison stems from the differences in the definition of inundated fraction. GIEMS dataset uses satellite observations at different wavelengths to derive the wetland area, while the CLM creates the surface inundation with the topography index and water inputs to the gridbox. Within the model parameterization, the height of the surface water level is calculated by a hypsometric function and the gridbox fraction is further derived from the grid size. This allows an ever-existing surface inundated fraction even in very dry gridboxes, whereas the GIEMS method underestimates the small wetlands comprising less than 10% of the gridbox area (Prigent et al., 2007); hence a model overestimation of satellite dataset is expected. Definition of modelled and satellite derived inundated fraction is not the same. Unfortunately there is no standard definition (Reichhardt, 1995), which produces the struggle to find a proper observational dataset to evaluate model results. What we emphasize from our findings is, nevertheless, the spatial patterns of higher inundated fractions occurring at similar locations in model and satellite dataset (Fig. 6).

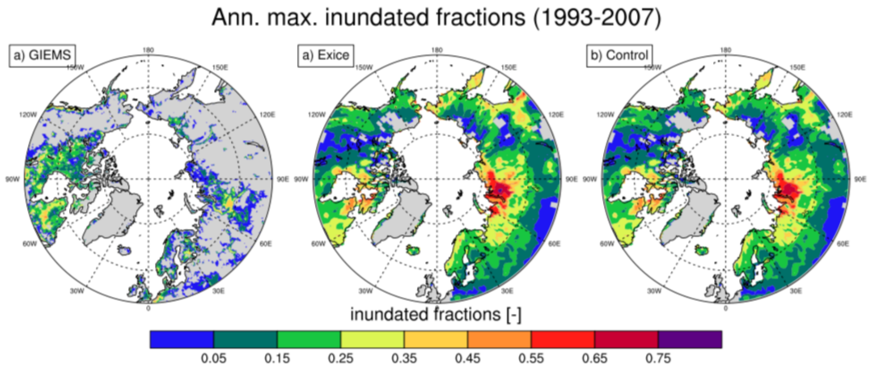

Fig. 6: Surface water fraction comparison from high latitude (>50°N) maps of annual maximum surface wetlands from GIEMS dataset (Prigent et al., 2012) and annual maximum f_{h2osfc} values of Exice and Control experiments for the period 1993-2007.

4. Conclusion

A warming climate affects the Arctic more severely than the rest of the globe. Increasing surface temperatures pose an important threat to the vulnerable high latitude ecosystems. Degradation of Arctic permafrost due to increased soil temperatures leads to the release of permafrost carbon to the atmosphere and further strengthens the greenhouse warming (IPCC, 2013; Schuur et al., 2008). For future climate predictions, it is necessary to properly simulate the Arctic surface inundated areas due to their physical and biogeochemical coupling with the atmosphere.

This study summarizes a new parameterization within the CLM to represent prognostic surface inundated fractions under permafrost thawing using a conceptual approach that can lead to implementation of a physical process-based parameterization. Coupling ground subsidence to surface microtopography distribution, hence allowing a natural link between surface hydrological conditions and soil thermodynamics, resulted in generally increased surface inundated fractions over the northern high latitudes, with larger surface inundated fractions around western and far-east Siberian plains and northeastern Canada. Projected increase in global temperatures will inevitably cause more excess ice melting and subsequent ground subsidence, therefore, it will be necessary to incorporate a process-based parameterization to accurately account for future ground subsidence effects on surface hydrological states.

Our results confirm the enhancements of coupling ground subsidence and surface inundation to represent the temporal changes in surface hydrology reflected by soil physical states and the atmospheric forcing, which is much needed for a future scenario experiment. Here we conclude that our new parameterization is implemented successfully and functions globally for the CLM model, that the inundated areas exist at the same areas as the observational data. It can be used for future climate scenarios such as shown in Lee et al. (2014) with major subsidence events during the 21st century under a high warming scenario.

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This new parameterization represents the first step into a process-based representation of such hydrological processes in CLM. Using this parameterization, further work can proceed to investigate the biogeochemical feedbacks of permafrost greenhouse gas fluxes between land and atmosphere.

Code and data availability

The code modifications to CLM model in accordance to this paper are accessible through the Zenodo archive with the following link:
https://zenodo.org/badge/latestdoi/183611414

The overall CLM model code can be obtained from the NCAR archives, the instructions on accessing the model code is given through this website:
http://www.cesm.ucar.edu/models/cesm2/land/

The full set of model data will be made publicly available through the Norwegian Research Data Archive at https://archive.norstore.no upon publication.

Author contribution

AE and HL designed the experiments and AE carried them out. DML and SCS developed the main CLM model code and HL developed the previous version this model is based on. CP has provided the GIEMS dataset. AE performed the simulations and prepared the manuscript with contributions from all co-authors.

Acknowledgements

This work was supported by the Research Council of Norway projects PERMANOR (255331) and MOCABORS (255061) and NSF EaSM-L02170157. The simulations were performed on resources provided by UNINETT Sigma2-the National Infrastructure for High Performance Computing and Data Storage in Norway, accounts NS2345K and NN2345K.

Supplementary

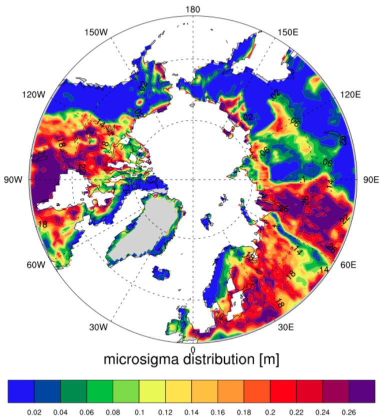

Fig. S1: High latitude (>50°N) map of default microsigma distribution.

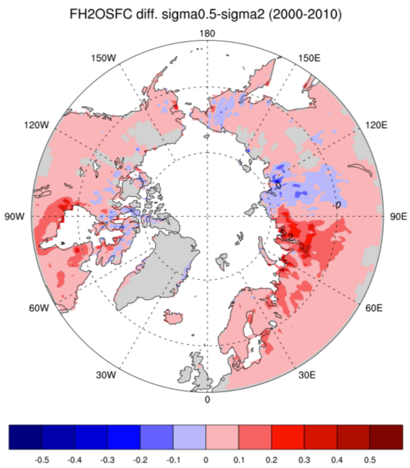

Fig. S2: Fh2osfc difference between Sigma-0.5 and Sigma-2 experiments.

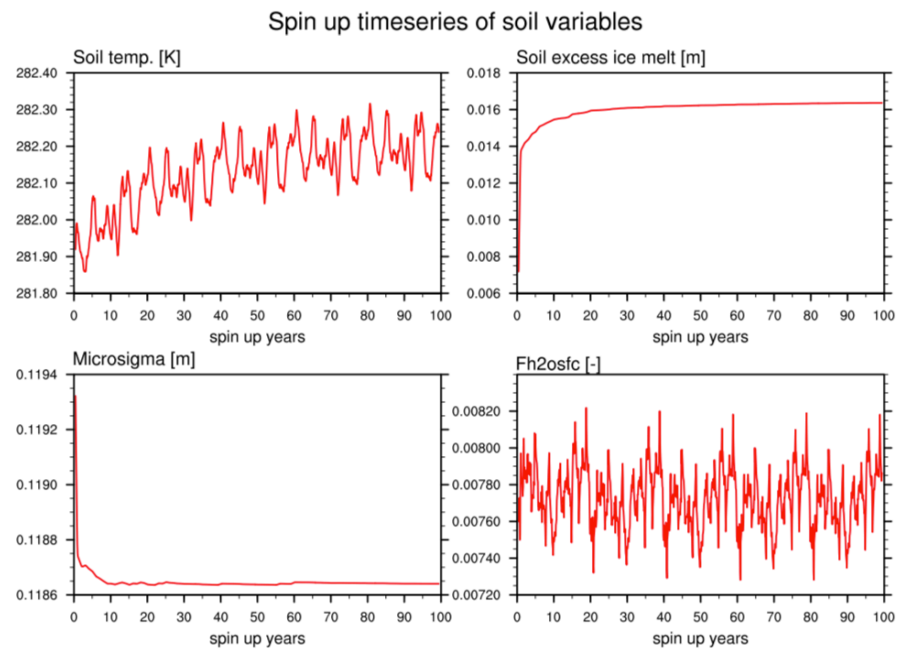

Fig. S3: 100 year spin up timeseries of spatially averaged soil physical variables related to the new parameterization.

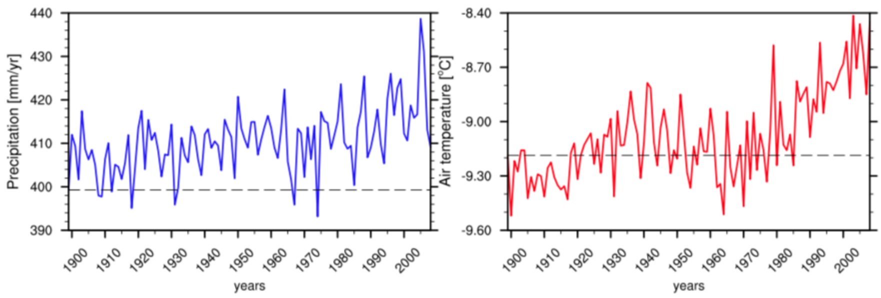

Fig. S4: Timeseries of high latitude (>50°N average -land only) CRUNCEP precipitation and air temperature forcing for the period 1900-2010. Dotted lines show 1900 value.

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