Author responses to reviewers in Andresen et al. “Soil Moisture and Hydrology Projections of the Permafrost Region: A Model Intercomparison”

REVIEWER #1

Dear Reviewer,
I sincerely appreciate taking the time to review this paper and provide very helpful comments and suggestions that significantly improved the clarity, flow and message of the manuscript. Below, I addressed every comment you had and responses are highlighted in blue.
Thank you.
Christian Andresen

Reviewer #1 Major issues:
1. Definition of permafrost in land models
In figure 1, it is unclear that if all soil layers showing here are hydrologically-active or not. I think authors here show all soil layers since for some models the soil layers areas deep as 47 meters, while in the figure caption authors call the figure “soil hydrological column configuration”. As bedrock layers do not involve in hydrological processes, authors should make clear in the figure how many layers for each model are hydrologically active. More importantly, this unclear statement raises a question in the definition of permafrost in this study. In section 2.2 (line 122), the authors define permafrost grid points with ALT less than 3 meters. However, for some models (JULES, TEM, and UWVIC) showing in Figure 1, the deepest soil layer is less than 3 meters deep. Then how permafrost is defined in these three models? Furthermore, comparisons are somewhat unreasonable because of the way authors define permafrost regions in these 8 models. Showing in Figure 3, the permafrost region actually differs substantially from models. ORCHIDEE has probably the biggest permafrost area globally while JULES has the smallest one. Different regions could correspond to different climate zones and climate changes associated with global warming. At least some differences showing in Figure 2 and 4 are originated from such different permafrost regions. Comparison over the overlapped regions with permafrost for all 8 models could be a more reasonable approach.

Authors response: These are important points that needed clarification in the manuscript. Thank you for highlighting them.

Changes:

-We modified the footnote of Figure 1 to clarify the hydrology layers of the models: “Figure 1. Soil hydrological-active column configuration for each participating model. Numbers and arrows indicate full soil configuration of models of non-hydrologically active bedrock layers. Colors represent the number of layers. “

-We also clarified the permafrost estimation for the top 3m soil column which is slightly different among models due to its soil configuration layers ranging from 2-3m. Line 123 now reads: “we define a grid cell as containing near-surface permafrost if the annual monthly maximum active layer thickness (ALT) is at or less than the 3m depth layer depending on the model soil configuration (Figure 1)”

-Regarding differences in permafrost extents across models, we decided to compare the full permafrost extent for each model rather than a subset to be representative for each model. The temperature (forcing) differences from the models, and thus, different areas, are shown in figure 2a and did not raised main concerns. However, we added clarification and highlighted this in the first paragraph of methods section 2.2: L121-123 “This qualitative hydrology comparison was based on the full permafrost domain in each model rather than a common subset among models in order to fully portray the overall changes in permafrost hydrology for participating models.”

2. Runoff in SIBCASA and other models Figure 6 & 7 show that the annual mean runoff in SIBCASA for the period of 1970-1999 is close to zero with little-to-none inter-annual variability, which is of course fairly biased from gauge station data. But in Table 3, there is also some (although not high) degree of correlation between observation and SIBCASA-simulated runoff. For the Mackenzie Basin, it is not even the lowest. The runoff of SIBCASA is more “flawed” than “low” to me. Authors should give an explanation/speculation of why SIBCASA simulates such abnormal runoff. Is there any systematic error or technical failure? Or the model itself does not involve runoff modeling? If there is systematic error in SIBCASA-simulated runoff, authors should exclude it from correlation coefficient analysis.

Another potential deficiency of this model-observation comparison is the inconsistency of forcing data. Previous studies, which have also mentioned by authors in the discussion section, have suggested that different forcing data, even for reanalysis datasets that are observational-restricted, can cause some substantial biases in modeled variables. Since runoff is largely dependent on precipitation that is directly from the forcing, some difference of inter-annual variabilities of runoff and their difference between gauge data should be attributed to the difference in precipitation forcing.

Authors response:

We clarified the issues of low runoff in SIBCASA in the results and excluded it from Figures 5, 6 & 7 to avoid confusion and make the paper clearer.

We kept SIBCASA in the correlation coefficient table 3 but highlighted that the analysis was for surface runoff only

Changes:

-Table 3 header: “Correlation coefficients between simulated annual total runoff and gauge mean annual discharge 1970 to 1999. SIBCASA correlations are for surface runoff.”

-We also added the following explanatory statement to the results:

L239- “SIBCASA horizontal subsurface runoff was disabled on the simulation because it tended to drain the active layer completely, resulting in very low and unrealistic soil moisture. Therefore, SIBCASA runoff values shown in this study are only for surface runoff.”

3. Discussion in the uncertainty of soil and hydrology simulations. In the cover letter, authors mentioned that one of the reviewers in the previous sub-mission rejected the manuscript partially because “The manuscript does not provide anything we don’t already know from the literature, i.e. that the model results vary depending on what model and forcing you use”. The authors tried to fix this issue by re-scoping the study and add discussions on the uncertainty of soil moisture and hydrology simulations. In my opinion, however, authors should work more to improve this part, showing how these differences contribute to the differed performances for different models

in the result section. Readers can actually expect all uncertainties authors discussed solely from Table 1 &2, where different numerical implementations are listed. Of course, models could differ substantially that may cause differences in model output. In section 4.2, authors should work more on linking the discussed uncertainty to the inter comparison results. For ex-ample, in line 317, the authors mentioned that involving organic matter could enhance drainage and redistribution of water in the soil column. Is there any evidence showing in the model intercomparison? Are models with organic matter involved showing greater drainage? And if not, is the signal covered up by some other more dominating physical processes? Similar discussion/comparison should be addressed as much as possible for all factors the authors mentioned in section 4.2. Otherwise, this part looks more like a literature review than discussion.

Authors response:

These are certainly important points for this study. Particularly, linking the uncertainty to differences processes will be very helpful for the science community. It is important to note that this study is a qualitative analysis (i.e. wetting vs drying) and does not focus on the details of magnitude and spatial patterns of the models signatures.

Nonetheless, the manuscript originally addressed some of the uncertainty sources (e.g. organic matter, runoff, etc) for each model with the help of the modeling groups as "potential" causes of performance. However, the first review of the manuscript was discontent with these speculations and the lack of evidence to support them. Pinpointing these processes directly was difficult and required additional simulations. Therefore, we removed these from the manuscript and we focused on the main modelling challenges (e.g. ALT, soil thermal dynamics, ET, etc.) and supported the statements with literature.

Changes:

To clarify and remind the reader the focus of the paper, we added the following sentence in the first paragraph of discussion L279-281:

"It is important to note that this study is more qualitative in nature and does not focus on the detail of magnitude or spatial patterns of model signatures."

Minor issues:

Figure 2: Why the precipitation for UWVIC behaves abnormally in the historical period, which decreases substantially between 1970 and 2000? As precipitation data is directly from the forcing data, authors should explain/discuss how the different forcing datasets in the historical period could bring biases to permafrost thermodynamics and hydrology, and if the biases in the historical period influence the simulation in the projected period.

Authors response:

Discussion of how different forcing datasets influence projections it is certainly an important topic. However, in this manuscript we focused on the overall trend of drying or wetting in these models rather than focusing in a lot of detail at the magnitude and/or spatial patterns of the model signatures.

No changes made

Figure 3: Specifically, for JULES, some Arctic coastal regions in Eurasia and Alaska are not defined as permafrost? Is it due to a lack of spatial resolution?

Authors response:

JULES is missing these cells in the future projections and thus, not added to the figure.

No changes made

Figure 4: The Y-axis ticks for ORCHIDEE should be changed to the same as other sub-figures.

Authors response:

Thanks for pointing that out, now all axes in figure 4 are identical
Table 3: P-values or significance tests should be addressed for these correlation coefficients.

Authors response:

We did ran significant tests for these correlations but did not added them.

Changes:

We added the stats to the figure and included the following statement in the footnote:

"Pearson correlations (*r*) significant at *p<0.01 and **p<2e-16. "

Discussion section: In my opinion, section 4.1 and 4.2 should switch. As section 4.2 is more closely related and more important to the intercomparison results. Section 4.1, on the other hand, discusses the feature most involved models have not supported yet.

Authors response:

We kept the "Permafrost degradation and drying" section first and details of uncertainty second given that this manuscript is a qualitative analysis of the trends and the causes of the trends (permafrost thaw and drying across all models).

No changes were made.

REVIEWER #2
Dear Reviewer,
I greatly appreciate taking the time to review this paper and provide very helpful comments and suggestions that significantly improved the clarity and message of the manuscript. Below, I addressed every comment you had and responses are highlighted in blue.
Thank you.
Christian Andresen

Major points Reviewer #2
Abstract. The last sentence is quite general and states things that are very well known already. Could the abstract instead finish with a more interesting statement pointing out specific knowledge gaps or recommended directions of research?
Authors response:
We agree and rewrote the last sentence of the abstract following your suggestion. Sentence now reads: "Coordinated efforts to address the ongoing challenges presented in this study will help reduce uncertainty in our capability to predict the future Arctic hydrological state and associated land-atmosphere biogeochemical processes across spatial and temporal scales".

106 Although method specifics can (hopefully) be obtained in the cited papers, I'd like a few more details here, for clarity. For one thing, it's not clear when the break point between historical, model-specific climate forcing and the common forcing took place. Was this at 1960 or at 2006?
Authors response:
We clarified the methods as suggested to include this detail:
L107 "simulations were conducted from 1960 to 2299, partitioned by an historic (1960-2009) and future simulation (2010-2299)".
114-117 Along the same lines, for clarity here: On what timescale did the historicalCCSM4 climate forcing repeat?
Authors response:
That was specific for each modeling group and addressed in McGuire *et al* 2018 (cited in manuscript).
134 Just to be clear, specify what years of model simulations were used for the comparison with 1970-1999 observations. I assume this is also long-term but is it the exact same period, or some other length?
Authors response:
We used the same years of simulations for comparison and highlighted it in the footnote of Figure 6 and 7.
Changes:
Figure 6. Runoff anomaly comparison between gauge data and models simulations for the period 1970-1999 mean.

157 Here the authors refer to the “permafrost domain”, but this is not clearly defined in methods. Please clarify in the methods sections whether the study domain is, for each model, all cells with near-surface permafrost above 45 degrees N, as suggested on lines 121-123, or something else.
Authors response:

This certainly needed clarification in the manuscript and we added/modified the following statements:

Changes:

In the first paragraph of methods section 2.2 we added: L121-123 “This qualitative hydrology comparison was based on the full permafrost domain in each model rather than a common subset among models in order to fully portray the overall changes in permafrost hydrology for participating models.”

We also clarified the permafrost estimation for the top 3m soil column which is slightly different among models due to its soil configuration layers ranging from 2-3m. Line 123-125 now reads: “we define a grid cell as containing near-surface permafrost if the annual monthly maximum active layer thickness (ALT) is at or less than the ~3m depth layer depending on the model soil configuration (Figure 1)”

168-171 I am a bit dubious as to whether these patterns hold over longer-term analysis. If this statement is supported by the comparison of 10-year averages shown in Figure3, I am unconvinced. See comment on that below. Figure 3. Here the authors use a ten-year period to illustrate long-term spatial changes. This is way too short as decadal variability is clearly substantial for some models (Figure 2c). This should be a 30-year period.
Authors response:
We agree, a 30-year period comparison will be more representative and strengthen the paper.
Changes:
We changed the analyses to 30 year averages and modified the figure 3 and 4 as suggested. No major changes were observed.

191-193 I think this statement is not supported enough by the data. Either there is a relationship or not, and it would be easier to determine the likelihood of that with a simple x-y plot of the data rather than these box plots. As the authors note, the UWVIC model is not useful at all for this question due to its resolution. But for the box plots shown, I think the SIBCASA model clearly shows no tendency for more drying with ALT increase, which is not acknowledged. The statement should be modified to moderate this claim somewhat. Also, I am wondering at the use of short time periods again here, and would prefer a 30-year period comparison.
Authors response:
We acknowledged that this is an important point that needed work and clarification. We are aware that these relationships are not straight forward and we highlighted it in the original text after our claim for fairness (L191-192). Original text reads: L192-195 “However, there is a large spread between soil moisture and ALT changes (Figure 4) which may be influenced by many interacting factors that can be difficult to assess directly and are out of the scope of this study.”

In addition, the reason why we did not use simple x-y plots was because boxplots were a clearer way to portray this trends and better shows the distribution of these points (compared to a scatterplot of 10,000 points).

Changes:

Following your suggestion, we strengthen the analysis by running the comparison analysis for a 30-year period and showed the correlation statistics for these relationships to support our statement.

222-223 According to the text, JULES exhibits the highest runoff increase with 0.8mm/day, but Figure 2g shows ORCHIDEE runoff increasing by 1.2 mm/day. Which is correct?

Authors response:

The statement only tries to convey that JULES has a high precipitation trend but does not imply it has the highest precipitation.

No changes made

Minor and language points

Authors response:

We made all the changes to the document following your suggestions and edits below.

110 The degree symbol seems to have been replaced by a 0 (zero character), at least on my computer.

161 Add "long-term" or "for the period after 2100" or similar to clarify that it's only after 2100 that most models stay on the drying side for soil moisture – up till then, about half of the models are close to zero change or wetting. I guess this is implicit with the talking of 2299 in the preceding sentence but still, just to be clear.

303 Change "large-scales" to "large scales".

392 Change "Study" to "The study".

Fig 1. The figure seems to show depths to 3.5 m but the caption says 3 m.

Fig 2. The caption says "Figures d, e, f, and g are represented as relative change from 1960 values". I think "relative change" implies a normalization which is not done here, so I suggest dropping "relative" from the above sentence.

Fig 7. At least in the pdf on my computer, the tick labels on the horizontal axis are misaligned and show up inside the plot instead of outside. Please check.

Soil Moisture and Hydrology Projections of the Permafrost Region: A Model Intercomparison

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Abstract. This study investigates and compares soil moisture and hydrology projections of broadly-used land models with permafrost processes and highlights the causes and impacts of permafrost zone soil moisture projections. Climate models project warmer temperatures and increases in precipitation (P) which will intensify evapotranspiration (ET) and runoff in land models. However, this study shows that most models project a long-term drying of the surface soil (0-20cm) for the permafrost region despite increases in the net air-surface water flux (P-ET). Drying is generally explained by infiltration of moisture to deeper soil layers as the active layer deepens or permafrost thaws completely. Although most models agree on drying, the projections vary strongly in magnitude and spatial pattern. Land-models tend to agree with decadal runoff trends but underestimate runoff volume when compared to gauge data across the major Arctic river basins, potentially indicating model structural limitations. Coordinated efforts to address the ongoing challenges presented in this study will help reduce uncertainty in our capability to predict the future Arctic hydrological state and associated land-atmosphere biogeochemical processes across spatial and temporal scales.

1. Introduction

Hydrology plays a fundamental role in permafrost landscapes by modulating complex interactions among biogeochemical cycling (Frey and Mcclelland, 2009; Newman et al., 2015; Throckmorton et al., 2015), geomorphology (Grosse et al., 2013; Kanevskiy et al., 2017; Lara et al., 2015; Liljedahl et al., 2016) and ecosystem structure and function (Andresen et al., 2017; Avis et al., 2011; Oberbauer et al., 2007). Permafrost has a strong influence on hydrology by controlling surface and sub-surface distribution, storage, drainage and routing of water. Permafrost prevents vertical water flow which often leads to saturated soil conditions in continuous permafrost while confining subsurface flow through perennially-unfrozen zones (a.k.a. taliks) in discontinuous permafrost (Jafarov et al., 2018; Walvoord and Kurylyk, 2016). However, with the observed (Streletskiy et al., 2008) and predicted (Slater and Lawrence, 2013) thawing of permafrost, there is a large uncertainty in the future hydrological state of permafrost landscapes and in the associated responses such as the permafrost carbon-climate feedback.

The timing and magnitude of the permafrost carbon-climate feedback is, in part, governed by changes in surface hydrology, through the regulation by soil moisture of the form of carbon emissions from thawing labile soils and microbial decomposition as either CO_2 or CH_4 (Koven et al., 2015; Schädel et al., 2016; Schaefer et al., 2011). The impact of soil moisture changes on the permafrost-carbon feedback could be significant. Lawrence et al. (2015) found that the impact of the soil drying projected in simulations with the Community Land Model decreased the overall Global Warming Potential of the permafrost carbon-climate feedback by 50%. This decrease was attributed to a much slower increase in CH_4 emissions if surface soils dry, which is partially compensated for by a stronger increase in CO_2 emissions under drier soil conditions.

Earth System Models project an intensification of the hydrological cycle characterized by a general increase in the magnitude of water fluxes (e.g. precipitation, evapotranspiration and runoff) in northern latitudes (Rawlins et al., 2010; Swenson et al., 2012). In addition, intensification of the hydrological cycle is likely to modify the spatial and temporal patterns of water in the landscape. However, the spatial variability, timing, and reasons for future changes in hydrology in terrestrial landscapes in the Arctic are unclear and variability in projections of these features by current terrestrial hydrology applied in the Arctic have not been well documented. Therefore, there is an urgent need to assess and better understand hydrology simulations in land models and how differences in process representation affect projections of permafrost landscapes.

Upgrades in permafrost representation such as freeze and thaw processes in the land component of Earth System Models have improved understanding of the evolution of hydrology in high northern latitudes. Particularly, soil thermal dynamics and active layer hydrology upgrades include the effects of unfrozen water on phase change, insulation by snow (Peng et al., 2015), organic soils (Jafarov, E. and Schaefer, 2016; Lawrence et al., 2008) and cold region hydrology (Swenson et al., 2012). Nonetheless, large discrepancies in projections remain as the current generation of models substantially differ in soil thermal dynamics (e.g. Peng *et al* 2015, Wang *et al* 2016). In particular, variability among current models simulations of the impact of permafrost thaw on soil water and hydrological states is not well documented. Therefore, in this study we analyze the output of a collection of widely-used "permafrost-enabled" land models. These models participated in the Permafrost Carbon Network Model Intercomparison Project (PCN-MIP) (McGuire et al., 2018, 2016) and contained the state-of the art representations of soil thermal dynamics in high latitudes at that time. In particular, we assess how changes in active layer thickness and permafrost thaw influence near-surface soil moisture and hydrology projections under climate change. In addition, we provide comments on the main gaps and challenges in permafrost hydrology simulations and highlight the potential implications for the permafrost carbon-climate feedback.

2. Methods

2.1 Models and Simulation Protocol

This study assesses a collection of terrestrial simulations from models that participated in the PCN-MIP (McGuire et al., 2018, 2016) (Table 1). The analysis presented here is unique as it focuses on the hydrological component of these models. Table 2 describes the main hydrological characteristics for each model. Additional details on participating models regarding soil thermal properties, snow, soil carbon and forcing trends can be found in previous PCN-MIP studies (e.g. McGuire *et al* 2016, Koven *et al* 2015, Wang *et al* 2016, Peng *et al* 2015). It is important to note that the versions of the models presented in this study are from McGuire *et al* (2016, 2018) and some additional improvements to individual models may have been made since then.

The simulation protocol is described in detail in *McGuire et al.*, (2016, 2018). In brief, models' simulations were conducted from 1960 to 2299, partitioned by an historic (1960-2009) and future simulation (2010-2299), ~~-~~forced with a common projected climate derived from a fully coupled climate model simulation (CCSM4) (Gent et al., 2011). Historic atmospheric forcing datasets (Table 1) (e.g. climate, atmospheric CO_2, N deposition, disturbance, etc.) and spin-up time were specific to each modeling group. The horizontal resolution (0.5°~~0~~ – 1.25°~~0~~) and soil hydrological column configurations (depths ranging from 2 to 47m and 3 to 30 soil layers) also vary across models (Figure 1). We focus on results from simulations forced with climate and CO_2 from the Representative Concentration Pathway (RCP) 8.5 scenario, which represents unmitigated, "business as usual" emissions of greenhouse gases. Future simulations were calculated from monthly climate anomalies for the Representative Concentration Pathway (RCP 8.5, 2006-2100) and the Extension Concentration Pathway (ECP 8.5, 2101-2299) scenarios overlaid by repeating historic forcing atmospheric datasets from CCSM4 (Gent et al., 2011).

2.2 Permafrost and Hydrology Variables Analyzed

Our analysis focused on the permafrost regions in the Northern Hemisphere north of 45^0N. This qualitative hydrology comparison was based on the full permafrost domain for each model rather than a common subset among models in order to fully portray the overall changes in permafrost hydrology for participating models. For each model, we define a grid cell as containing near-surface permafrost if the annual monthly maximum active layer thickness (ALT) is at or less than the 3m ~~in~~ depth layer depending on the model soil configuration (Figure 1) (McGuire et al., 2016; Slater and Lawrence, 2013). Participating models represent frozen soil for layers with temperature of <273.15°k, acting as an impermeable layer for liquid water. We assessed how permafrost changes affect near-surface soil moisture, defined here as the soil water content (kg/m^2) of the 0-20 cm soil layer. We focused on the top 20 cm of the soil column due to its relevance to near-surface biogeochemical processes. We added the weighted fractions for each depth interval to calculate near-surface soil moisture (0-20cm) to account for the differences in the vertical resolution of the soil grid cells among models (Figure 1). To better understand the causes and consequences of changes in soil moisture, we examined several principal hydrology variables including evapotranspiration (ET), runoff (R; surface and sub-surface) and precipitation (P; snow and rain). Representation of ET, R and soil hydrology varies across participating models and are summarized in table 2.

We compared model simulations with long-term (1970-1999) mean monthly discharge data from ~~(~~Dai *et al* 2009~~)~~. We computed model mean annual discharge including surface and subsurface runoff for the main river basins in the permafrost region of North America (Mackenzie, Yukon) and Russia (Yenisei, Lena). Gauge stations from major permafrost river basins used for simulation comparison include (i) Arctic Red, Canada (67.46^{0}N, 133.74^{0}W) for Mackenzie River, (ii) Pilot Station, Alaska (61.93^{0}N 162.88^{0}W) for Yukon River, (iii) Igarka, Russia (67.43^{0}N, 86.48^{0}E) for Yenisey River and (iv) Kusur, Russia (70.68^{0}N, 127.39^{0}E) for Lena River.

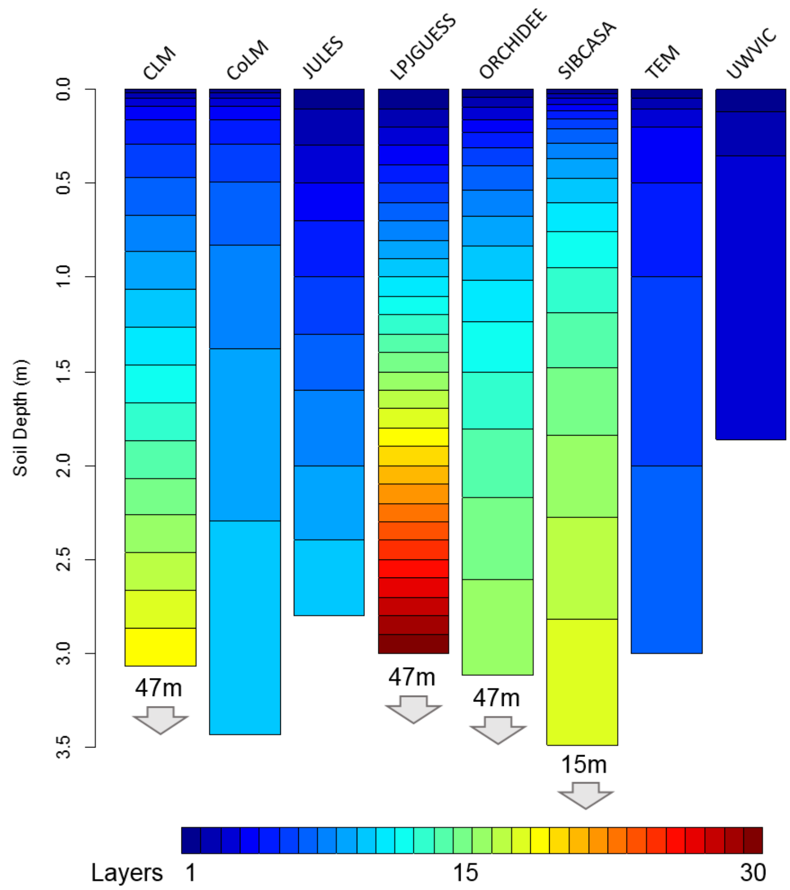


Figure 1. Soil hydrological<u>**ly-active**</u> **column configuration** ~~**used in**~~ <u>**for**</u> **each** <u>**participating**</u> **model** ~~**for the top 3 m**~~**. Numbers and arrows indicate** <u>**full soil configuration of non-hydrologically active bedrock layers**</u>~~**models with configurations deeper than 3 meters**~~**. Colors represent the number of layers.**

Table 1. Models description and driving datasets.

Model	Full Name	Climate Forcing Dataset	Model Reference	Short-Wave radiation[a]	Long-Wave Radiation[a]	Vapor Pressure[a]
CLM 4.5	Community Land Model v4.5	CRUNCEP4[b]	Oleson *et al* (2013)	Yes	Yes[c]	Yes

CoLM	Common Land Model	Princeton[d]	Dai *et al* (2003), Ji *et al* (2014)	Yes	Yes	Yes
JULES	Joint UK Land Environment Simulator model	WATCH (1901-2001)[e]	Best *et al* (2011)	Yes	Yes	Yes
ORCHIDEE-IPSL	Organising Carbon and Hydrology In Dynamic Ecosystems	WATCH (1901-1978)[e]	Gouttevin, I. *et al* (2012), Koven *et al* (2009), Krinner *et al* (2005)	Yes	Yes	Yes
LPJGUESS	Lund-Postdam-Jena dynamic global veg model	CRU TS 3.1[f]	Gerten *et al* (2004), Wania *et al* (2009b, 2009a)	Yes	No	No
SiBCASA	Simple Biosphere/Carnegie-Ames-Standford Approach model	CRUNCEP4[b]	Schaefer *et al* (2011), Bonan (1996), Jafarov, E. and Schaefer (2016)	Yes	Yes	Yes
TEM604	Terrestrial Ecosystem Model	CRUNCEP4[b]	Hayes *et al* (2014, 2011)	Yes	No	No
UW-VIC	Univ. of Washington Variable Infiltration Capacity model	CRU[f], Udel[h]	Bohn *et al* (2013)	Internally calculated	Internally calculated	Yes

[a]Simulations driven by temporal variability

[b]Viovy and Ciais (http://dods.extra.cea.fr/)

[c]Long-wave dataset not from CRUNCEPT4

[d]Sheffield *et al* (2006) (http://hydrology.princeton.edu/data.pgf.php)

[e]http://www.eu-watch.org/gfx_content/documents/README-WFDEI.pdf

[f]Harris *et al* (2014), University of East Anglia Climate Research Unit (2013)

[g]Mitchell and Jones (2005) for temperature

[h]Willmott and Matsuura (2001) for wind speed and precipitation with corrections (see Bohn et al. 2013).

Table 2. Hydrology and soil thermal characteristics of participating models.

	Hydrology								Soil Thermal Properties			
Model	Evapotranspiration approach	Root water uptake	Infiltration	Water table	Soil Water Storage and Transmission	Groundwater Dynamics	Soil-ice impact	Snow	Soil thermal dynamics approach	Unfrozen Water effects on Phase Change	Moss insulation	Organic soil insulation
CLM 4.5	Sum of canopy evaporation, transpiration, and soil evaporation	Macroscopic approach	Saturation-excess runoff $F_{sat}=f(z_{wt})$	Niu et al. (2007); perched water table possible if ice layer present	Richard's equation (Clapp Hornberger functions)	Base flow from TOPMODEL concepts, unconfined aquifer (Niu et al. 2007)	Impacts hydrologic properties through power-law ice impedance (Swenson et al., 2012)	Multi-layer dynamic (5 max)	Multi-layer Finite Difference Heat Diffusion	Yes	No	Yes
CoLM	BATS and Philip's (1957)	Macroscopic approach	Saturation-excess runoff $F_{sat}=f(z_{wt})$	Simple TOPMODEL	Richard's equation (Clapp Hornberger functions)	Base flow from TOPMODEL	Impacts hydrologic properties through power-law ice impedance	Multi-layer dynamic (5 max)	Multi-layer Finite Difference Heat Diffusion	No	No	No
JULES	Sum of ET, soil evaporation and moisture storages (e.g. lakes, urban) minus surface resistance	Macroscopic approach	Saturation-excess runoff $F_{sat}=f(z_{wt})$ or $F_{sat}=f(\theta)$	TOPMODEL or Probability Distribution Model	Richard's equation (Clapp Hornberger/van Genuchten functions)	Base flow from TOPMODEL	Hydraulic conductivity and suction determined by unfrozen water content (Brooks and Corey functions)	Multi-layer dynamic (3 max)	Multi-layer Finite Difference Heat Diffusion	Yes	No	No
ORCHIDEE-IPSL	Sum of bare soil, interception loss and plant transpiration for different veg PFTs in grid cell.	Macroscopic approach, water uptake different among cell veg PFTs (de Rosnay and Polcher, 1998)	Saturation-excess runoff $F_{sat}=f(\theta)$	TOPMODEL	Richard's equation (van Genuchten functions)	None	"Drying=Freezing" approximation (Gouttevin et al 2012)	Multi-layer dynamic (7 max)	1D Fourier Solution	Yes	No	Yes
LPJ-GUESS	Sum of Interception loss, plant transpiration and evaporation from soil. Gerten et al (2004)	Fractional water uptake from different soil layers according to prescribed root distribution. (Wania et al., 2009a,b)	Depends on soil moisture and layer thickness. Declines exponentially with soil moisture	Uniform, and only for wetland grid cell (Wania et al., 2009a,b)	Analog to Darcy's Law, percolation rate depends on soil texture conductivity and soil wetness (Haxeline and Prentice, 1996).	Base flow is based on the exponential function to estimate percolation rate	Impacts hydrologic properties through power-law ice impedance	Multi-layer dynamic (3 max)	Multi-layer Finite Difference Heat Diffusion	No	No	No
SiBCASA	Sum of ground evaporation, surface dew, canopy ET and canopy dew (Bonan, 1996)	Macroscopic approach	Infiltration approach in non-saturated porous media described by Darcy's law	Niu et al. (2007); perched water table possible if ice layer present	Richard's equation (Clapp Hornberger functions)	Base flow from TOPMODEL concepts, unconfined aquifer (Niu et al. 2007)	Impacts hydrologic properties through power-law ice impedance	Multi-layer dynamic (5 max)	Multi-layer Finite Difference Heat Diffusion	Yes	No	Yes
TEM-604	Jenson-Haise potential ET (PET, Jenson and Haise 1963). Actual ET is calculated based on PET, water availability and leaf mass.	Based on the proportion of actual ET to potential ET	Field capacity-excess runoff (Thornthwaite and Mather 1957)	none	one-layer bucket	none	none	Multi-layer dynamic (9 max)	Multi-layer Finite Difference Heat Diffusion	No	Yes	No
UW-VIC	Sum of canopy interception, veg. transpiration and soil evaporation (Liang et al. 1994)	Based on reference ET and soil wilting point	Saturation-excess runoff $F_{sat}=f(\theta)$	Microtopography	From infiltration rate and infiltration shape parameter (Liang et al. 1994). No lateral flow between model grids	Base flow from Arno model conceptualization (Francini and Pacciani 1991)	Impacts hydrologic properties through power-law ice impedance	Bulk-layer dynamic (2 max)	Multi-layer Finite Difference Solution	Yes	No	Yes

2. Results

3.1 Soil Moisture

Air temperature forcing from greenhouse-gas emissions shows an increase of ~15^{o}C in the permafrost domain over the simulation period (Figure 2a). With increases in air temperature, models project an ensemble mean decrease of ~13 million km^2 (91%) of the permafrost domain by 2299 (Figure 2b). Coincident with these changes, most models projected a long-term drying of the near-surface soils when averaged over the permafrost landscape (Figure 2c). However, the simulations diverged greatly with respect to both the permafrost-domain average soil moisture response and their associated spatial patterns (Figure 2c, 3). The models' ensemble mean indicated a change of -10% in near-surface soil moisture for the permafrost region by year 2299, but the spread across models was large. COLM and LPJGUESS simulate an increase in soil moisture of 10% and 48%, respectively. CLM, JULES, TEM6 and UWVIC exhibit qualitatively similar decreasing trends in soil moisture ranging between -5% and -20%. SIBCASA and ORCHIDEE projected a large soil moisture change of approximately -50% by 2299. Spatially, models show diverse wetting and drying patterns and magnitudes across the permafrost zone (Figure 3). Several models tend to get wetter in the colder northern permafrost zones and are more susceptible to drying along the southern permafrost margin. Other models, such as TEM6 and UWVIC show the opposite pattern with drying more common in the northern part of the permafrost domain.

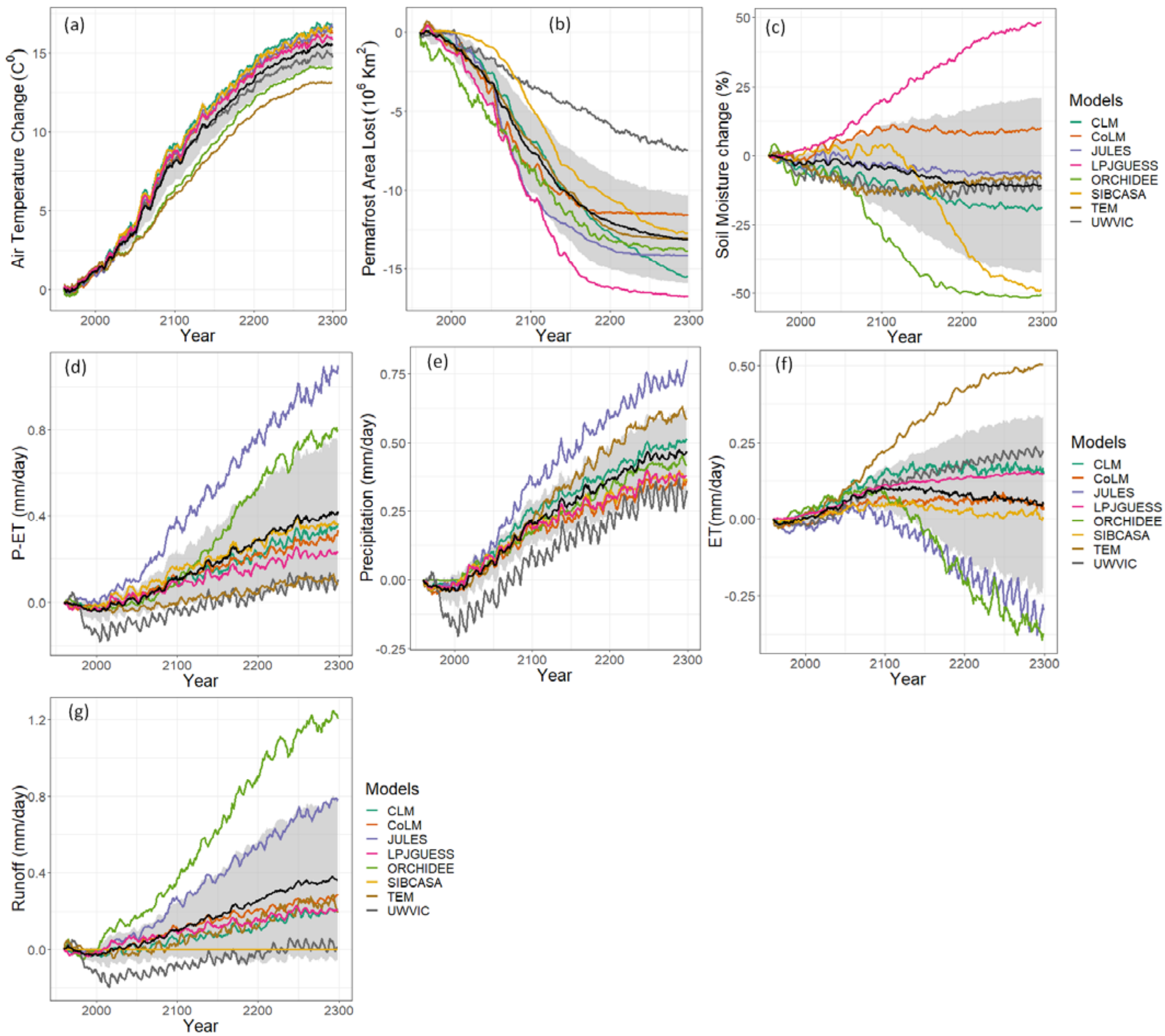
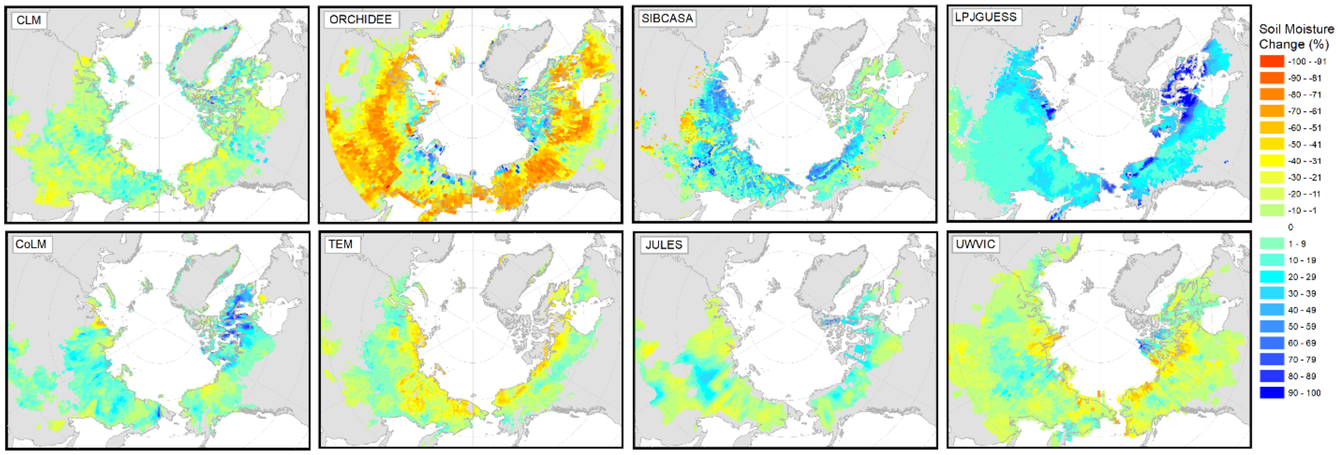


Figure 2. Simulated annual mean changes in air temperature, near-surface permafrost area, near-surface soil moisture and hydrology variables relative to 1960 (RCP 8.5). Annual mean is computed from monthly output values. The black line represents the models' ensemble mean and the gray area is the ensemble standard deviation. Figures d, e, f, and g are represented as ~~relative~~ change from 1960 values. Time series are smoothed with a 7-year running mean and calculated over the initial permafrost domain of each model in 1960 for latitude >45^{0}N.



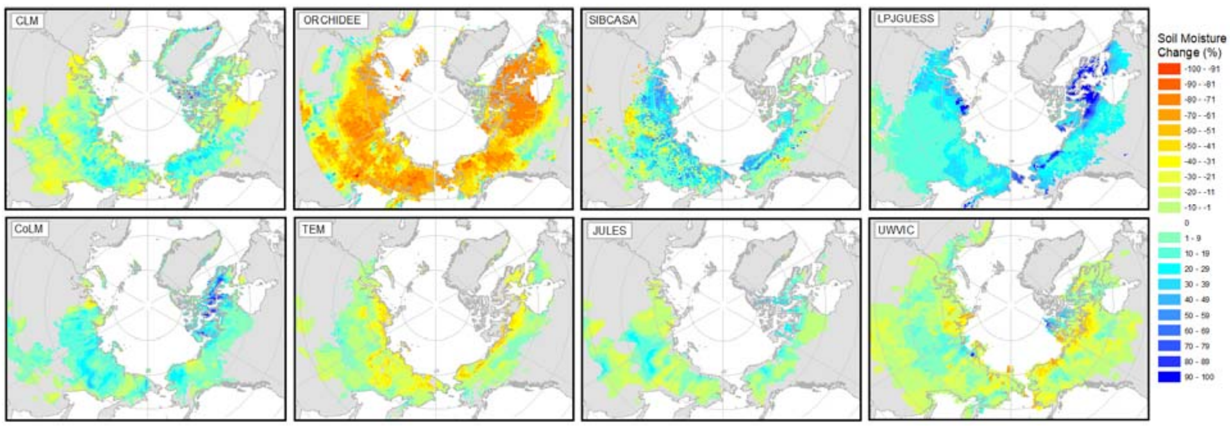
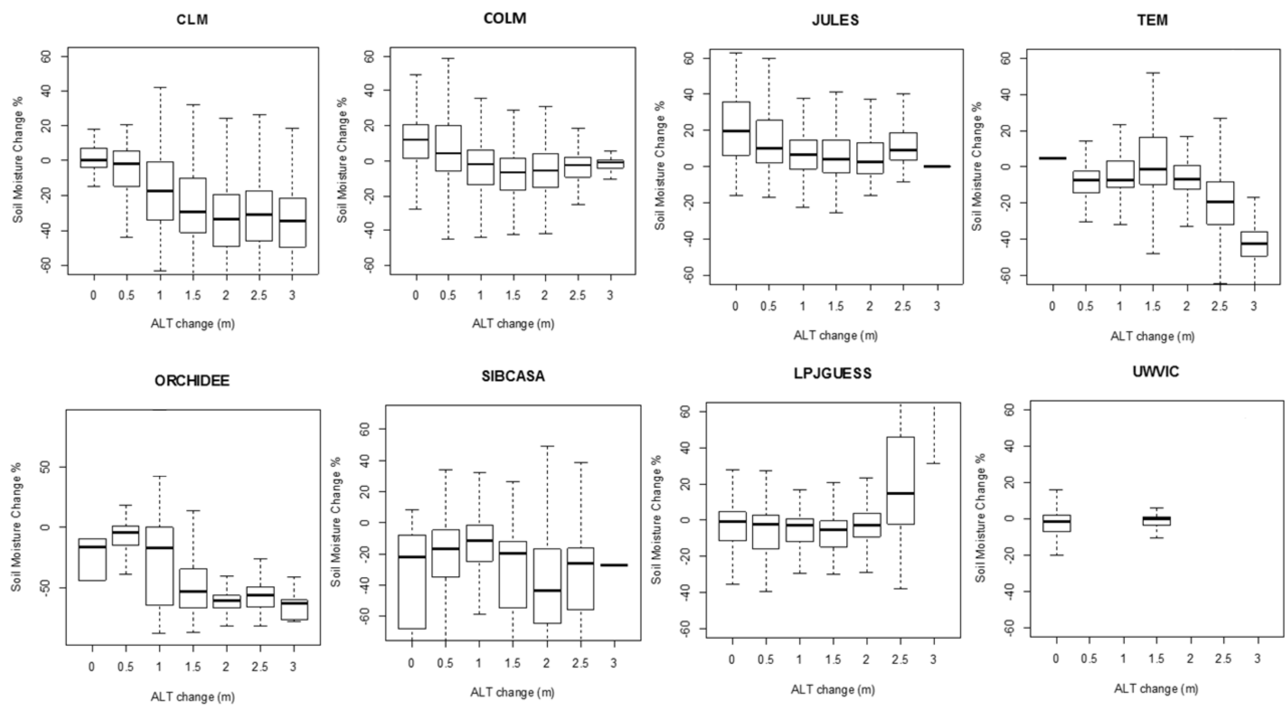


Figure 3. Spatial variability of projected changes in surface soil moisture (%) among models. Depicted changes are calculated as the difference between the ~~2091~~ 2071 to 2100 average and the 1960 to ~~1969~~ 1989 average. Colored area represents the initial simulated permafrost domain of 1960 for each model.

3.2 Drivers of Soil Moisture Change

To understand why models projected upper soil drying despite increases in the net precipitation (P-ET) into the soil, we examined whether or not increases in active layer thickness (ALT) and/or complete thaw of near-surface permafrost could be related to surface soil drying of the top 0-20cm ALT. We observed a general significant negative trend in most models, except SIBCASA, LPJGUESS and UWVIC, where cells with greater increases in active layer thickness have greater drying (decrease) in near-surface soil moisture (Figure 4). However, there is a large spread between soil moisture and ALT changes (Figure 4). This spread may be influenced by many interacting factors that can be difficult to assess directly and are out of the scope of this study. In addition, the coarse soil column discretization in UWVIC limited this analysis for this model (Figure 1). However, most models show some indication that as the active layer deepens, soils tend to get drier at the surface.



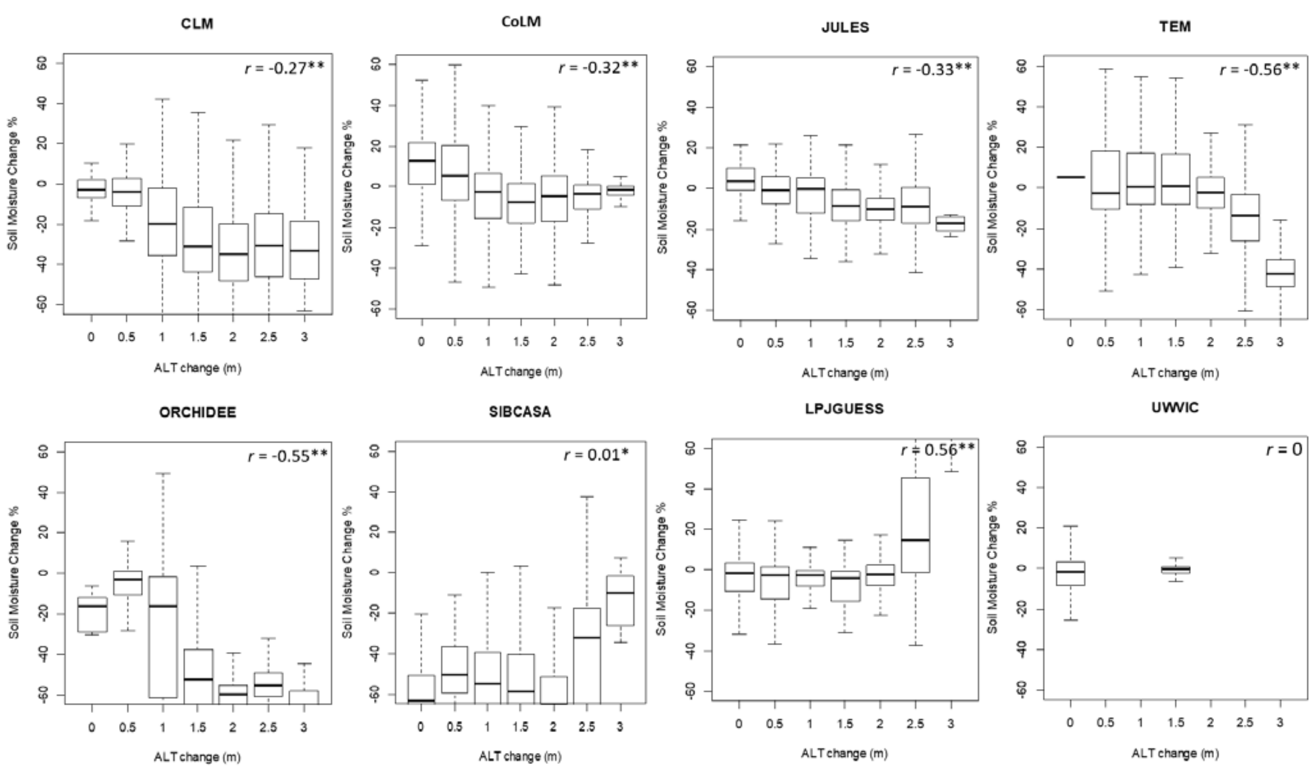


Figure 4. Responses of August near-surface (0-20cm) soil moisture to ALT changes. Each box represents a range of ±0.25m of ALT change. ALT and soil moisture change are calculated as the 2290-2299 average minus the 1960-~~1969~~ 1989 average for cells in the initial permafrost domain of 1960. For cells where ALT exceeded 3 meters (no permafrost) during ~~2290~~2270-2299 period, we

subtracted the initial active layer thickness (1960-~~1969~~ 1989 average) to 3 meters. Pearson correlations (*r*) significant at *p<0.01 and **p<2e-16.

3.3 Precipitation, ET, and Runoff

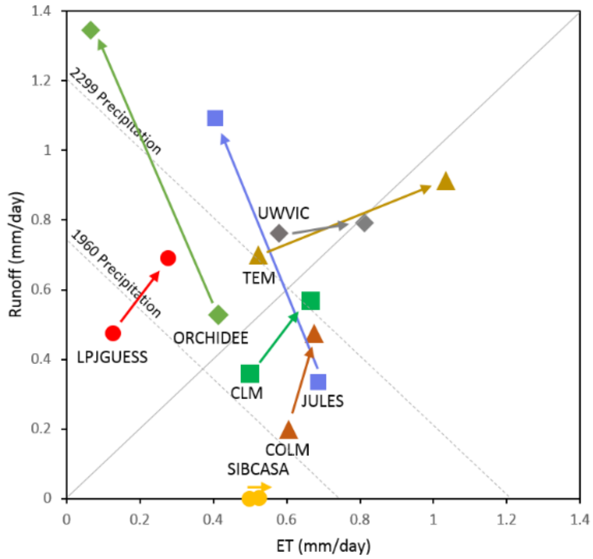
Models may project surface soil drying but the hydrological pathways through which this drying occurs appears to differ across models. The diversity of precipitation partitioning (Figure 5) demonstrates that specific representations and parameterizations for ET and runoff are not consistent across models. Though some models maintain a similar R/P ratio throughout the simulation (e.g., CLM, COLM, LPJGUESS), others show shifts from an ET-dominated system to a runoff-dominated system (e.g. JULES) and vice versa (e.g. TEM6 and UWVIC).

Evapotranspiration from the permafrost area is projected to rise in all models driven by warmer air temperatures and more productive vegetation, but the amplitude of that trend varies widely. The average projected evapotranspiration increase is 0.1±0.1mm/day by 2100, which represents about a 25% increase over 20th century levels. Beyond 2100, the ET projections diverge (Figure 2e).

Runoff is also projected to increase with projections across models being highly variable (Figure 2g). The change in the models' ensemble mean between 1960-2299 was 0.2±0.2 mm/day. CLM, COLM, LPJGUESS and TEM6 simulated runoff changes of 0.2 to 0.3 mm/day by 2299. ~~SIBCASA and~~ UWVIC exhibit small to null changes in runoff while SIBCASA shows surface runoff only. JULES exhibited the highest runoff change with +0.8 mm/day for 2299, consistent with its high applied precipitation trend.

Comparison between gauge station data and runoff simulations from the major river basins in the permafrost region shows that most models agree on the long term timing (Figure 6, Table 3) but the magnitude is generally underestimated (Figure 7). The gauge discharge mean for the four river basins is 219 ± 36 mm/yr compared to the models' ensemble mean of 101 ± 82 mm/yr for the period 1970-1999. Excluding ~~the low runoff of~~ SIBCASA, the models' ensemble mean is 134 ± 69 mm/yr. However, models show reasonable correlations between runoff output and observed annual discharge time series (Table 3). SIBCASA horizontal subsurface runoff was disabled on the simulation because it tended to drain the active layer completely, resulting in very low and unrealistic soil moisture. Therefore, SIBCASA runoff values shown in this study are only for surface runoff.

The net water balance (P-ET-R) is projected to increase for most models with precipitation increases outpacing the sum of ET and runoff changes. All models except TEM6 show an increase in the net water balance over the simulation period which suggests that models are collecting soil water deeper in the soil column, presumably in response to increasing ALT, even while the top soil layers dry.



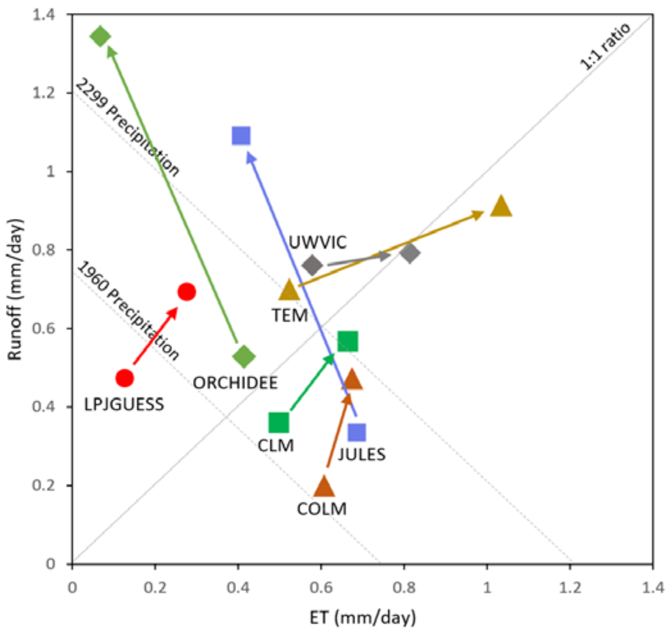
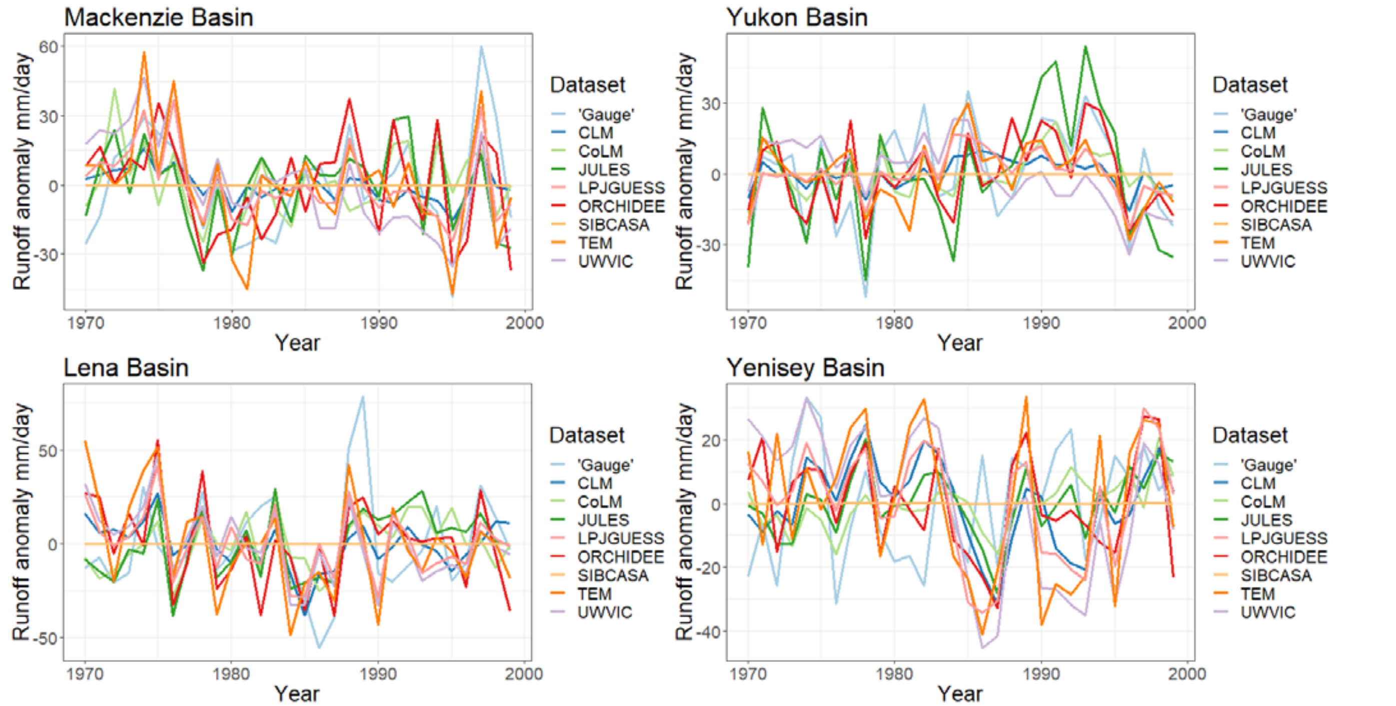


Figure 5. Precipitation partitioning between total runoff and evapotranspiration for participating models. Markers and arrows indicate the change from initial period (1960-1989 average) to final period (2270-2299 average). Diagonal dashed lines represent the ensemble rainfall mean for the initial (0.74 mm/day) and final (1.2 mm/day) simulation years. At any point along the dashed diagonals, runoff and ET sum to precipitation.



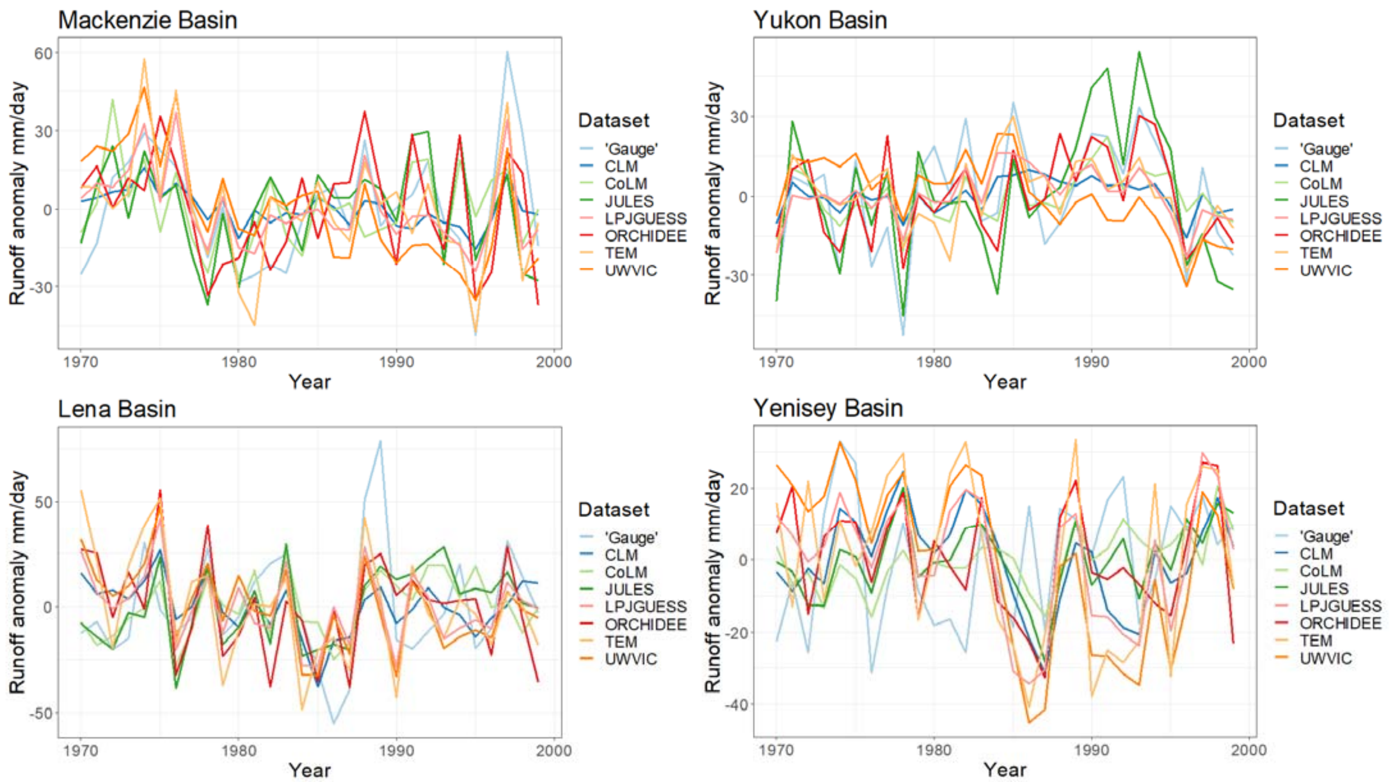
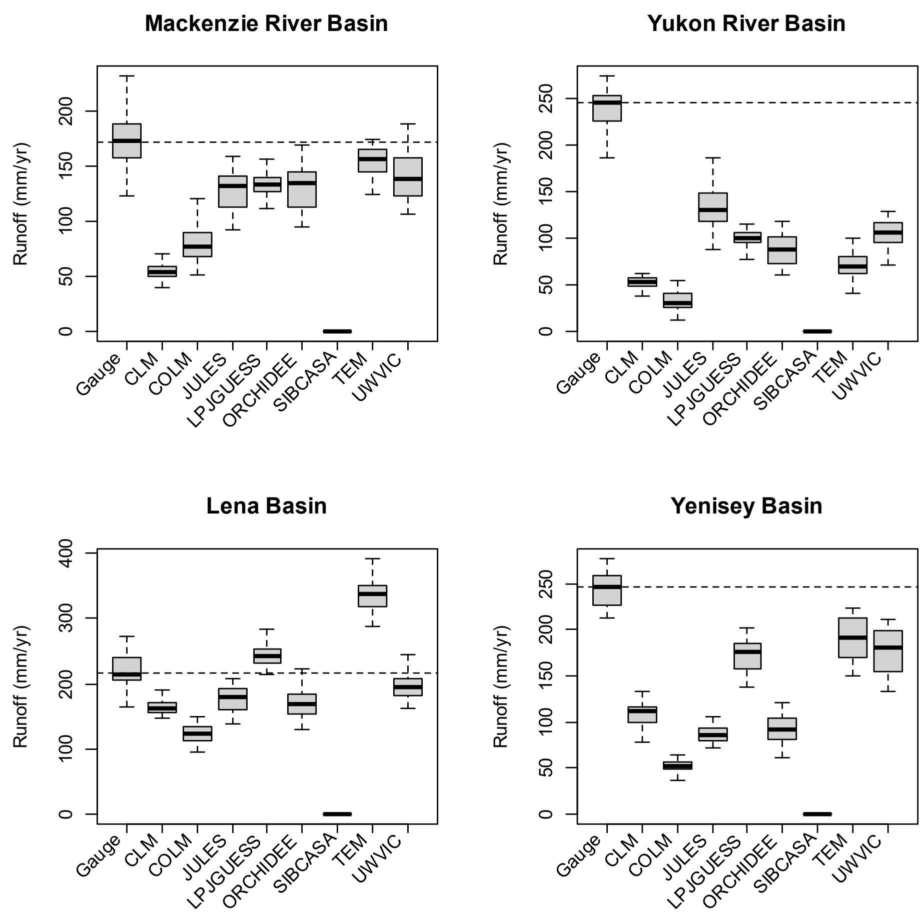


Figure 6. Runoff anomaly ~~from 1970-1999 mean~~ comparison between gauge data and models simulations for the period 1970-1999 mean.

Table 3. Correlation coefficients between simulated annual total runoff and gauge mean annual discharge 1970 to 1999. SIBCASA correlations are for surface runoff.

	River Basin				
Model	Mackenzie	Yukon	Yenisey	Lena	Avg.
CLM	0.70	0.64	0.08	0.46	0.47
ORCHIDEE	0.57	0.69	0.36	0.37	0.50
LPJGGUESS	0.68	0.71	0.14	0.35	0.47
TEM	0.66	0.56	0.16	0.40	0.45
SIBCASA	0.49	0.21	0.08	0.29	0.27
JULES	0.41	0.77	0.34	0.51	0.51
COLM	0.38	0.76	0.27	0.46	0.47
UWVIC	0.44	0.38	0.02	0.31	0.29
Avg.	0.54	0.59	0.18	0.40	



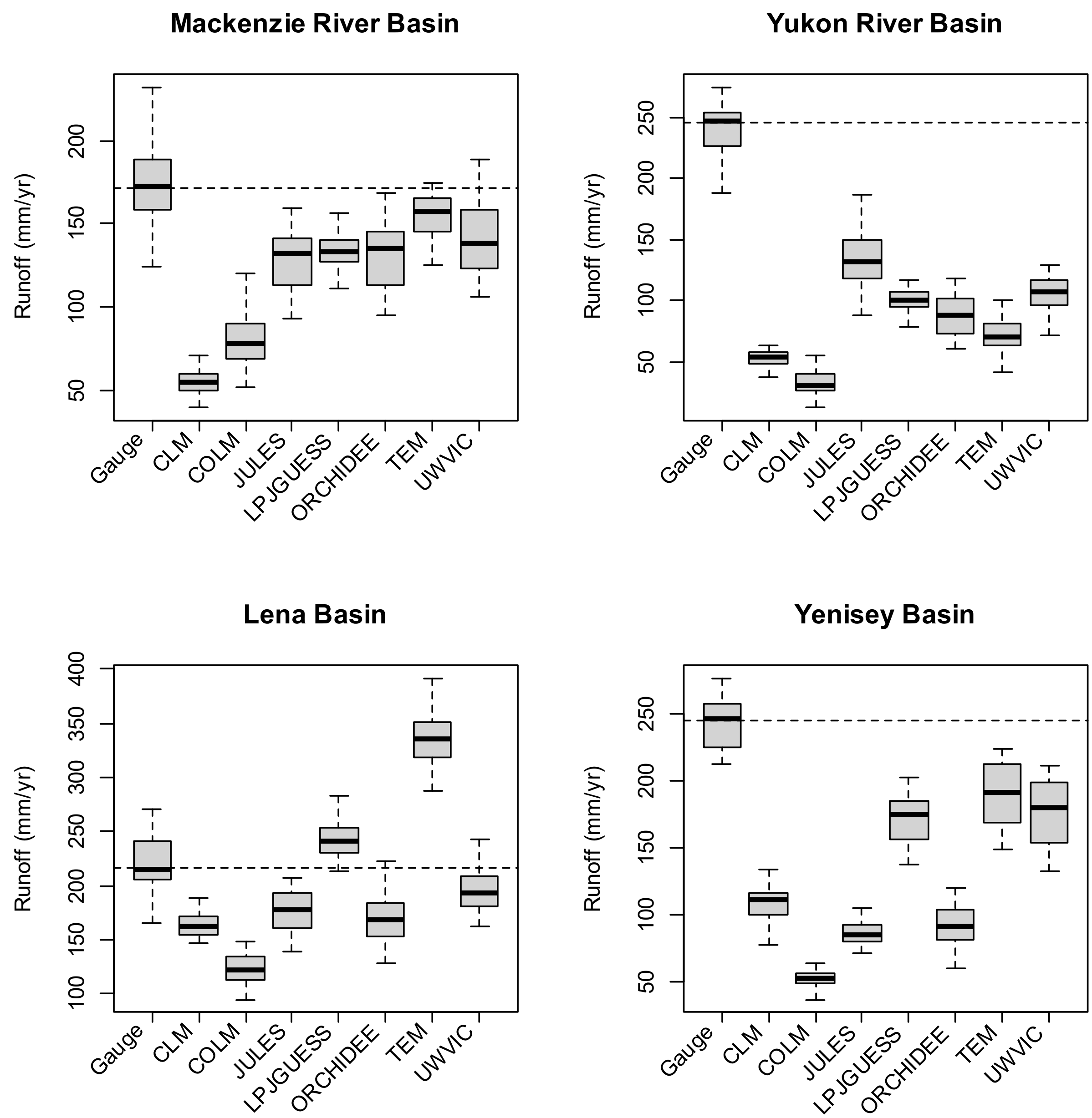


Figure 7. Discharge comparison between gauge station data and model output for each river basin. Dashed line indicates mean annual discharge at gauge station. Boxplots derived from mean annual discharge (total runoff) simulations for the period of 1970 to 1999.

4. Discussion

This study assessed near-surface soil moisture and hydrology projections in the permafrost region using widely-used land models that represent permafrost. Most models showed near-surface drying despite the externally-forced intensification of the water cycle driven by climate change. Drying was generally associated with increases of active layer thickness and permafrost degradation in a warming climate. We show that the timing and magnitude of projected soil moisture changes vary widely across models, pointing to an uncertain future in permafrost hydrology and associated climatic feedbacks. In this section, we review the role of projected permafrost loss and active layer thickening on soil moisture changes and some potential sources of variability among models. In addition, we comment on the potential effects of soil moisture projections on the permafrost carbon-climate feedback. It is important to note that this study is more qualitative in nature and does not focus on the detail of magnitude or spatial patterns of model signatures.

4.1 Permafrost degradation and drying

Increases in net precipitation and the counterintuitive drying of the top soil in the permafrost region suggests that soil column processes such as changes in active layer thickness (ALT) and activation of subsurface drainage with permafrost thaw are acting to dry the top soil layers (Figure 8a). In general, models represent impermeable soils when frozen. Then, as soils thaw at progressively depths in the summer, liquid water infiltrates further into the active layer draining deeper into the thawed soil column (Avis et al., 2011; Lawrence et al., 2015; Swenson et al., 2012). However, relevant soil column processes related to thermokarst by thawing of excess ground ice (Lee et al., 2014) are limited in these simulations despite their significant occurrence in the permafrost region (Olefeldt et al., 2016). As permafrost thaws, ground ice melts, potentially reducing the volume of the soil column and changing the hydrological properties of the soil (Aas et al., 2019; Nitzbon et al., 2019). This would occur where soil surface elevation drops through sudden collapse or slow deformation by an amount equal to or greater than the increased depth of annual thaw (Figure 8b). This mechanism, not represented in current large-scale models, could result in projected increases or no change in the water table over time as observed by long-term studies (Andresen and Lougheed, 2015; Mauritz et al., 2017; Natali et al., 2015). Subsidence of 12-13 cm has been observed in Northern Alaska over a five year period, which represents a volume loss of about 25% of the average ALT for that region (~50cm) (Streletskiy et al., 2008). These lines of evidence may suggest that permafrost thaw may not dry the Arctic as fast as simulated by land models but rather maintain or enhanced soil water saturation depending on the water balance of the modeled cell column.

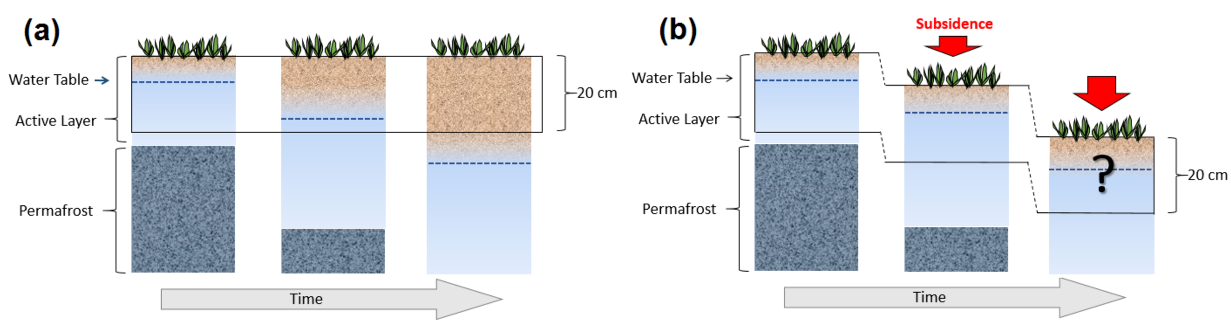


Figure 8. Schematic of changes in the soil column moisture (a) without subsidence (current models) and (b) with subsidence from thawing ice-rich permafrost (not represented by models), a process that may accumulate soil moisture and slow down drying over time.

Recent efforts have been made to address the high sub-grid heterogeneity of fine-scale mechanisms including soil subsidence (Aas et al., 2019), hillslope hydrology, talik and thermokarst development

(Jafarov et al., 2018), ice wedge degradation (Abolt et al., 2018; Liljedahl et al., 2016; Nitzbon et al., 2019), vertical and lateral heat transfer on permafrost thaw and groundwater flow (Kurylyk et al., 2016) and lateral water fluxes (Nitzbon et al., 2019). These processes are known to have a major role on surface and subsurface hydrology and their implementation in large scale models is needed. Other important challenges in land models' hydrology include representation of the significant area dynamics of the ubiquitous smaller, shallow water bodies observed over recent decades (Andresen and Lougheed, 2015; Jones et al., 2011; Roach et al., 2011; Smith et al., 2005). These systems are either lacking in simulations (polygon ponds and small lakes) or assumed to be static systems in simulations (large lakes). The implementation of surface hydrology dynamics and permafrost processes in large-scale land models will help reduce uncertainty in our ability to predict the future hydrological state of the Arctic and the associated climatic feedbacks. It is important to note that all these processes require data for model calibration, verification and evaluation, that is commonly absent at large-scales. Permafrost hydrology will only advance through synergistic efforts between field researchers and modelers.

4.2 Uncertainty in soil moisture and hydrology simulations

Differences in representations of soil thermal dynamics can directly affect hydrology through timing of the freezing-thawing cycle and by altering the rates of permafrost loss and subsurface drainage (Finney et al., 2012). McGuire et al. (2016) and Peng et al. (2016) show that these models exhibit considerable differences in permafrost quantities such as active layer thickness, and the mean and trends in near-surface (0-3m) permafrost extent, even though all the models are forced with observed climatology. However, these differences are smaller than those seen across the CMIP5 models (Koven et al., 2013). All models except ORCHIDEE employ a multi-layer finite difference heat diffusion for soil thermal dynamics (Table 2). Organic soil insulation, snow insulation, and unfrozen water effects on phase change are the most common structural differences among models for soil thermal dynamics but do not explain the variability in the simulated changes in ALT and permafrost area as shown by McGuire *et al* (2016). Half of the participating models include organic matter in the soil properties (CLM, ORCHIDEE, SIBCASA, UWVIC) which can significantly impact soil thermal properties and lead to an increase in the hydraulic conductivity of the soil column, thereby enhancing drainage and redistribution of water in the soil column. Soil vertical characterization is another important aspect for soil thermal dynamics and hydrology (Chadburn et al., 2015; Nicolsky et al., 2007). Lawrence et al (2008) indicated that a high-resolution soil column representation is necessary for accurate simulation of long term trends in active layer depth. However, McGuire *et al* (2016) showed that soil column depth did not clearly explain variability of the simulated loss of permafrost area across models.

Water table representation can result in a first order effect on soil moisture. Most models (CLM, COLM, SIBCASA and ORCHIDEE) use some version of TOPMODEL (Niu et al., 2007), which employs a prognostic water table where sub-grid scale topography is the main driver of soil moisture variability in the cell. However, water table is not explicitly represented in other models such as LPJGUESS, which has a uniform water table which is only applied for wetland areas. In addition to water table, storage and transmission of water in soils is a fundamental component of an accurate representation of soil moisture (Niu and Yang, 2006). The representation of soil water storage and transmission varies across models from Richards equations based on Clapp Hornberger and/or van Genuchten (1980) functions (e.g CLM, CoLM, SIBCASA, ORCHIDEE) to a simplified one layer bucket (e.g. TEM6). It is also important to note that most models differ in their numerical implementations of processes, such as water movement through frozen soils (Gouttevin, I. et al., 2012; Swenson et al., 2012), and in the use of iterative solutions and vertical discretization of water transmission (De Rosnay et al., 2000).

Differences in representation of vertical fluxes through evapotranspiration (ET) are also likely adding to the high variability in soil moisture projections. ET sources (e.g. interception loss, plant transpiration, soil evaporation) were similar across models but had different formulations (Table 2). The diversity of ET implementations (e.g. evaporative resistances from fractional areas, etc.) and of vegetation maps used by the modelling groups (Ottlé et al., 2013) can also contribute to the big spread on the temporal simulations for ET and soil moisture. Along with projected increases in ET, net precipitation (P-ET) is projected to increase for all models suggesting that drying is not attributed only to soil evaporation, and the increasing net water balance (P-ET-R) proposes that models are storing water deeper in the soil column as permafrost near the surface thaws.

Despite runoff improvements (Swenson et al., 2012), underestimation of river discharge has been a challenge in previous versions in models (Slater et al., 2007). The differences between models and observations in mean annual discharge may stem from several sources. Particularly, the substantial variation in the precipitation forcing for these models (Figure 2e). This is attributed, in part, to the sparse observational networks in high latitudes. River discharge at high latitudes can differ substantially when different reanalysis forcing datasets are used. For example, river discharge for Arctic rivers differs substantially in CLM4.5 simulations when forced with GSWP3v1 compared to CRUNCEPv7 reanalysis datasets (not shown, runoff for MacKenzie, +32%; Yukon, +78%; Lena, -2%; Yenisey, +22%). Other factors include potential deficiencies in the parameterization and/or implementation of ET and runoff processes as well as vegetation processes.

4.3 Implications for the permafrost carbon-climate feedback

If drying of the permafrost region occurs, carbon losses from the soil will be dominated by CO_2 as a result of increased heterotrophic respiration rates compared to moist conditions (Elberling et al., 2013; Oberbauer et al., 2007; Schädel et al., 2016). With projected drying, CH_4 flux emissions will slow down by the reduction of soil saturation and inundated areas through lowering the water table in grid cells (Figure 8A). In a sensitivity study using CLM, the slower increase of methane emissions associated with surface drying could potentially lead to a reduction in the Global Warming Potential of permafrost carbon emissions by up to 50% compared to saturated soils (Lawrence et al., 2015). However, we need to also consider that current land models lack representation of important CH_4 sources and pathways in the permafrost region such as lake and wetland dynamics that can counteract the suppression of CH_4 fluxes by projected drying. Seasonal wetland area variation, which is not represented or is poorly represented in current models, can contribute to a third of the annual CH_4 flux in boreal wetlands (Ringeval et al., 2012). Although this manuscript may raise more questions than answers, this study highlights the importance of advancing hydrology and hydrological heterogeneity in land models to help determine the spatial variability, timing, and reasons for changes in hydrology of terrestrial landscapes of the Arctic. These improvements may constrain projections of land-atmosphere carbon exchange and reduce uncertainty on the timing and intensity of the permafrost carbon feedback.

Data availability

The simulation data analyzed in this manuscript is available through the National Snow and Ice Data Center (NSIDC; http://nsidc.org). Inquires please contact Kevin Schaefer (kevin.schaefer@nsidc.org).

Author contributions

This manuscript is a collective effort of the modeling groups of the Permafrost Carbon Network (http://www.permafrostcarbon.org). C.G.A, D.M.L., C.J.W., A.D.M. wrote the initial draft with additional contributions of all authors. Figures prepared by C.G.A.

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