We appreciate the helpful comments and suggestions by the three referees. Below we provide responses to the comments and indicate where changes to the manuscript were made.

**Review #1**

This paper presents interesting results from a hydrological modeling study examining how runoff partitioning from arctic catchments is changing. The authors present an updated version of the Pan-Arctic Water Balance Model to better represent soil freeze-thaw processes and have renamed it the Permafrost Water Balance Model version 3 (PWBM v3). In general, the authors use the model to demonstrate that cold season discharge and groundwater flows are increasing in four arctic basins underlain by continuous permafrost. The authors do a very nice job of characterising how runoff and terrestrial water storage is changing in arctic catchments. This study is limited to basins underlain by continuous permafrost and differs from other work in that they do not attempt to generalise findings from large northern regions spanning different permafrost distributions (which is a good thing). The results and discussion are limited explicitly to model outputs, which are supported by only basic model validation from observed measurements. Without a better understanding of how the model performs, it is difficult to determine how valid the model outputs are, as well as potential errors associated with the outputs. Additionally, the novelty of this study is questionable as the main conclusion of this paper (as is stated many times in the discussion) is that arctic catchments are exporting increased runoff via subsurface pathways, which has previously been demonstrated in the literature. I think that this modeling study could been important contribution; however there are several significant revisions and additions that are required.

Major Points: A major weakness of this manuscript is the lack of model validation and performance evaluation. At this point it is impossible to understand how well the model performs, and consequently impossible to comment on whether the outputs area realistic interpretation of the physical system. By only discussing the outputs of the model there is potential for a large disconnect between what is being presented and the system for which the authors are trying to represent. Why is only one basin (Kuparuk)used for validation? There are other suitable gauged basins by the United States Geological Survey and the Water Survey of Canada that could be used as validation. This component is crucial to the success of the paper. The only validation presented in the results section states that freshet volume was similar, yet even on a monthly time step the model performance is weak (~30% error in both May and June). If the authors want to describe how the partitioning of runoff is changing by exclusively examining model outputs then it is imperative to prove that the model can simulate observations. To do this, it is necessary to use a finer resolution than monthly time-steps.

We appreciate the review of our manuscript. We have revised the draft to include additional validation comparisons with observed data, and the manuscript now includes a model validation section. Line 253. We have added a validation against river discharge for the Colville River. In the validation section we show that average active layer thickness closely matches estimates from another model (GIPL) developed at the Permafrost Laboratory, Geophysical Institute at the University of Alaska-Fairbanks. The PWBM captures the expected north-south spatial gradient, as does GIPL. In the validation section we also show and describe a comparison with SWE data across the Kuparuk basin. Model simulated end of season SWE is correlated ($r = 0.78$, $p < 0.01$) with the observations. The model captures interannual variability. For validation we then show a significant correlation ($r = 0.74$ , $p < 0.001$) with measured Kuparuk River discharge. The time series plot confirms that the model well represents the correct magnitude and interannual variability based on measured data. The error in May and June arises due to peak discharge in the model simulation that is approximately 8 days early compared to the observations. The total simulated discharge over the freshet period May and June has low error of just +0.3%. The freshet period is also well resolved for the Colville River, with error of 10%. The model is run at a daily time step. We disagree that accurate daily resolution in the evaluations is required. On the contrary, with a goal to quantify seasonal export of constituents such as dissolved organic carbon and other nutrients, reasonably well constrained monthly climatologies and well correlated interannual variability is sufficient. My coauthors and other colleagues have discussed this issue at great length. The processes leading to the changes we describe in this paper arise largely due to long-term warming, which was substantial over the region, some 4.5 F warming over the 30 year period 1981-2010. How well the model simulates runoff on a daily basis has little bearing on its ability to simulate the processes fundamental to the myriad changes observed by other researchers and simulated via the PWBM. We will add that the study domain extends only a short distance into Canada, and we are aware of no observed discharge data for the small rivers in that area. We feel that we have a robust model validation given the paucity of spatially extensive data available in this region. Paragraph at lines 328-340 details the available long-term data for the largest rivers.

Why is modeled cold season discharge not evaluated against observations? Surely USGS publishes this data.

No consistent observations exist for discharge during the Nov-Apr period for any North Slope river, with the exception of the Kuparuk. Our goal in this work is to quantify and understand the freshwater export for the North Slope region. While we always seek more data with which to evaluate and better understand shortcomings in the approaches, in the end we believe that a numerical model must be used to obtain regional estimates for cold season discharge. Validation at that scale is obviously quite limited.

Why is there no model performance evaluation? There are many different evaluation techniques (e.g. Nash-Sutcliffe Efficiency, Root Mean Square Error, Percent Bias, Kling-Gupta Efficiency), but none are presented in the paper, nor is the reader referenced to other papers where they may be presented.

The model performance evaluation is based on the average error, percentage error, and correlation. Line 241. Model evaluation metrics based on squared values, like the RMSE, are known to be biased. We cite Willmott et al., 2005 and Willmott et al., 2015. Line 244.

Willmott, C.J. and Matsuura, K., 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate research*, *30*(1), pp.79-82.

Willmott, C.J., Robeson, S.M., Matsuura, K. and Ficklin, D.L., 2015. Assessment of three dimensionless measures of model performance. Environmental Modelling & Software, 73, pp.167-174.

Is there any model calibration? Are there any empirical factors used? More information is needed.

Empirical factors have been described in prior published studies: Rawlins et al., 2003, 2013 and Yi et al., 2015. Two parameters we adjusted in this study as calibration. They involve runoff and evaporation from the surface pool. We have added language that the model calibration involved the surface storage pool and the river flow routing. Lines 213-217. Please also see our responses below.

This manuscript describes intensification of the hydrological cycle and is supported through re-analysis data and modeling efforts. The manuscript would benefit from supporting data from observations. It would be useful to plot precipitation from climate stations across Alaska and northern Canada to prove this, as well as using or referencing snow survey data. Modeling these changes is important, however these modeled changes need to be supported by observations.

Intensification is first mentioned in the Introduction, as it is an important element of climate change. We include snow survey data. Shown in Figures S3 and S4. The study domain entends mere kilometers into Northern Canada, near the coast, and there are no weather stations in that small area just west of the Mackenzie delta. Our introductory information regarding hydrological cycle intensification reflects the findings from earlier published studies. We state that no significant change occurred over the North Slope study region over the 30 years period 1981-2010. Line 320. Interannual variability renders the small time changes as insignificant. Our results are independent of time changes in precipitation.

The authors use much of the discussion to suggest that the proportion of groundwater runoff is increasing, yet there is very little discussion of how the structure of these flowpaths is changing. As the study sites located exclusively in continuous permafrost. I would assume that these changes would be through supra-permafrost groundwater flow, but this is not explicitly stated.Is the ice-rich transient layer (Shur et al., 2005, Permafrost and Periglacial Processes,10.1002/ppp.518) accurately represented in the model? This ice-rich layer retards active layer thickening due to the high latent heat requirements for thaw, and would also provide an additional water source once thawed.

Yes. The model captures the saturated ice-rich conditions at the top of the permafrost. In the PWBM there are 10 layers spanning the upper 3 m of the soil model soil column. Low hydraulic conductivity results in high water content in the uppermost permafrost. In fact, the ability of the PWBM to capture the zero curtain effect, the processes of phase change resulting in a long period time where soil stays near 0 C during thaw and freeze, was described recently by Yi et al. (2019) which we cite. Results shown in Figure 9 and 10 and described at lines 394-405 suggest a connection between a deepening of the soil active layer and increasing subsurface flow. This is likely due to increased storage of water into fall that allows for runoff generation. As we point out, losses in soil ice also contribute to runoff. Further study is required to test the first process. The paper includes an extensive discussion of study results in the context of other recent work.

Does changing seasonality of precipitation affect runoff generation? Some sentences are taken directly from other papers. These sentences should be changed in an attempt to synthesize other literature. For example, lines 436-39: “St. Jacques and Sauchyn concluded that increases in winter baseflow and mean annual streamflow in the NWT were caused predominantly by climate warming via permafrost thawing that enhances infiltration and deeper flowpaths and hydrological cycle intensification (Frey and McClelland, 2009; Bring etal., 2016)”. This text appears almost exactly word-for-word in the abstract of that paper. I also find it odd that a sentence from another paper has two additional references after it. Actually, St. Jacques and Sauchyn (2009) propose reactivation of deep groundwater flowpaths by making linkages between streamflow and climate. Also, many of the basins in this study are underlain by discontinuous permafrost, which would promote recharge of sub-permafrost groundwater aquifers that provide baseflow to rivers, a process not applicable in thick, continuous permafrost. Again, the changing physical processes need to be explored.

Characterization of seasonal precipitation change is beyond the scope of our study. We mention in the Discussion that changes in seasonality may play a role in the trends documented in our study. Line 555-557. We agree that permafrost thawing may be enhancing infiltration and promoting deeper flowpaths. We have re-worded the statement where St. Jacques and Sauchyn (2009) study was cited. Line 479. The information is appropriate. For a region of largely discontinuous permafrost these important processes would be occurring across a land unit defined by the presence of permafrost, such as a north facing slope. Observations (eg Jorgenson et al., 2008 http://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Front_Dec2008_Jorgenson_etal_2008.pdf) show that the entire North Slope domain is underlain by continuous permafrost. Our results point to a deepening of the soil active layer which is leading to increased flow in the thawed zone, contributing to enhanced subsurface runoff generation. Losses in soil ice which outweigh gains in liquid storage also contribute to the increasing fraction of subsurface runoff as a proportion of total annual runoff. The Discussion section includes perspective on changing physical processes. Line 501-514. Also line 521 and line 529.

If the authors are going to validate and calibrate model, why only use it for a period in the past? Analysis of past data can be conducted reasonably well with measured data. The authors may be better served to also use the model as a predictive tool to demonstrate how a changing climate may affect the streamflow regime of arctic rivers.

We appreciate the suggestion. However, the comment is invalid. There is an extreme lack of measured data in this region. Our study focus is on characterizing the baseline hydrology for the area of northern Alaska draining to the Beaufort Sea coast, for the 30 year period 1981-2010, and on understanding changes that are occuring. It is not possible to do this from the few observations. For example, river discharge has been measured at the Kuparuk River near the coast for several decades. The Colville River has been monitored since only 2002, but not in every month. Aside from those two rivers, long term records, to our knowledge, do not exist. Measurements in the cold season, when low flows exist under river ice cover, are virtually non existent. Information on data for these rivers has been added at paragraph starting at line 328.

The figures need substantial revision and improvement. They are not suitable for publication in their current form. The authors should provide a study site map delineating all four watersheds, as well as a layer identifying each underlying permafrost zone.

New map of the study domain has been added. Results maps include outlines of the Colville, Kuparuk, and Sagavanirktok rivers to aid in interpretation of results. The region is one single zone of continuous permafrost.

Line 108 states that the study area is underlain by continuous permafrost. Is this the case for the entire study site?

Yes. All prior studies published by other researchers for this part of Alaska suggest continuous permafrost is present over the entirety of our study domain.

Figure 1 is a very important figure and does not suffice as model validation. For example, the figure should be presented on a daily time-step (not aggregated into monthly intervals) to demonstrate how the model captures individual events. For example, there are substantial differences between May and June runoff, suggesting that the hydrological behaviour of the basin may not be captured.

We have added a new section on Model Validation including daily average discharge for the Kuparuk and Colville rivers. However, to quantify seasonal export of constituents such as dissolved organic carbon and other nutrients, reasonably well constrained monthly climatologies and well correlated interannual variability are sufficient. We contend that the results shown in the new section clearly demonstrate that the model simulations are valid.

Also, all time series plots should include each data point instead of a continuous line-graph. The dashed-line in the simulation makes it difficult to observe performance. The formatting of all figures should be improved in this manner.

Figures have been modified accordingly.

Figure 4 should present discharge normalised over basin area. As a result, the North Slope shows disproportionately more discharge due to the much larger basin area. I am not sure why the authors decided to present the data this way, considering that Figure 1 presents normalised runoff. Also, the current format-ting makes it next to impossible to discern runoff trends for the three smaller basins.

We disagree. Our intent for this figure, in part, is to help illustrate the differences in discharge volume flux for those rivers, and show them in relation to total discharge for the full North Slope domain. This has relevance for the export of river-borne constituents. The volumes are not so different as to require displaying in unit depth. Average values are listed in Table 2. The trends and their statistical significance are described in the text. We do not feel that a separate figure panel is needed.

Figure 5 is slightly misleading as the plot only shows the grid cells with significant changes.

We disagree that illustrating the magnitude of change for grid cells bearing significant change is misleading. We have re-drawn the plot to include all grid cells, and it simply shows many dots overlapping one another near zero change. The analysis and significance are clear. To our knowledge it is not uncommon to present information in this manner.

Figure 6 shows that many grid cells do not have significant change – but Figure 5 suggests that there is an increasing proportion of subsurface runoff in June and decreasing in July, when in fact these proportions may be relatively constant if the whole dataset it included.

We’ve made no statement that our results suggest that the proportion of subsurface runoff has increased for averages across the entire North Slope. Figure 6 is for annual runoff (subsurface and total). Figure 5 is for months May to September, and annual. The figures are fundamentally different, and complementary.

Minor Points: Line 21: Can you better define region based on watersheds?

New map (Figure 1) shows the study region, which we define as all land areas draining to the Beaufort Sea coast, not including the Mackenzie River basin.

Line 21: Do not need the word ‘annually”, this is given in your units.

Word ‘annually’ removed.

Line 22: Is this volume derived from modeled results or gauges? If the former, this needs to be stated, if the latter, these gauges should be used for validation

The baseline river discharge estimates now include both measured and model simulated data. Phrase “A synthesis of measurements and model simulations …” added. Line 22.

Line 24: The authors need a better preface for their results. At this point it is unknown what the results are describing.

“Our results...” changed to “The simulations...”. Line 24.

Line 34: I am not convinced that this shift is representative of the physical system, given section 3.3 states errors in freshet timing. Again, displaying data on a daily time step for all basins would be beneficial.

New figure 3 shows simulated and measured at a daily time step for the two rivers where evaluation is possible. NOAA data (Climate at a Glance Tool (https://www.ncdc.noaa.gov/cag/divisional/time-series/5001/tavg/2/5/1981-2010?trend=true&trend_base=10&firsttrendyear=1981&lasttrendyear=2010) shows that air temperature averaged across the North Slope has warmed in April-May (average) by 5.4 F. We believe that warming in late spring is resulting in earlier snowmelt and, in turn, the timing of peak discharge. Proving this is beyond the scope of the present study. Timing for the Colville River is well captured. The bias in simulated time of peak discharge is assumed based on comparison with Kuparuk River gauge data is inherently part of the uncertainty in our reported trend in timing of peak discharge for the region as a whole. We agree that the uncertainty in timing is considerable. But we are convinced that the shift is real. That said, we are prepared to drop that result from the paper. We are in the process of improving the snowmelt sub-model which should improve timing based on comparisons with measured daily discharge.

Line 47: Provide references for “mean freshwater budgets across the land”.

That statement is backed by the cited Serreze et al. (2006) paper. We are unaware of any other studies that examine the mean freshwater budgets across the land, atmosphere and ocean domains.

Line 52: This sentence is redundant given the previous sentence.

Sentences combined: A warming climate is expected to lead to intensification of the hydrological cycle, including increases in net precipitation (P) at high latitudes, and evidence is emerging (Peterson et al., 2002, 2006; Rawlins et al., 2010; Zhang et al., 2013; Bring et al., 2016). Line 51.

Lines 53-55: What about shorter ice duration on lakes and longer seasons for evaporation?

We now mention these processes in a subsequent sentence. Line 56.

Lines 69-71: This areal loss of permafrost applies to sporadic and discontinuous permafrost. The study site described by the authors indicates very thick continuous permafrost. This discussion should be limited to continuous permafrost environments so that the physical processes occurring in different environments are not confused.

That citation is early in the Introduction section and speaks broadly to permafrost loss in general, so we feel it would be helpful to the reader. We are not opposed to removing it. In areas where permafrost is discontinuous, the relevant hydrological changes to which we refer are taking place locally where permafrost is present. For example, on north-facing slopes, or where soil carbon amounts are high.

Lines 75-77: Similar comment to above, most of the rivers described in the cited studies are either subarctic or underlain by discontinuous permafrost. Runoff generation is very different between the two environments and this needs to be stated if there is extensive discussion about these systems.

In areas of discontinuous permafrost, where land units contain permafrost, the runoff generating processes would be similar. In areas where much of the landscape is defined by the absence of permafrost, runoff generation processes can be much different from areas where permafrost is nearly continuous. Sentence on runoff generation and discontinuous permafrost areas added at line 83.

Line 95: Why do you need to leverage a modeling framework to investigate changes in peak daily discharge? Would observational daily data not be a better method for this?

There is an extreme paucity of river discharge measurements at the mouths of North Slope rivers. It is clear that a better understanding of changes in the timing of peak discharge, at the coast, for this 196,000 km2 region, can only be obtained via advanced numerical modeling.

Lines 108-110: The study area is underlain by thick, continuous permafrost. This context needs to be explored in more depth in the discussion. The authors should describe how the flowpaths in this environment would differ from other studies in the literature. This has the potential to be a novel contribution and differentiate this work from other studies that it cites.

We have added detail and depth to the paragraph in the Summary and Discussion. Line 501. Additional language has been added through that section. Our focus is on mechanisms operating in regions of largely continuous permafrost.

Line 112: Provide a table of all observational data, agency responsible for collecting the data, locations of data collection, and period of data record.

We used observational data for SWE and river discharge. It is not clear that a Table would be helpful for just two data sets. We point the reader to the USGS data online. Details on the SWE data has been added in section 2 on Study Area, Data and Modeling. Starting at line 104.

Lines 157-159: I am not sure I understand this sentence. How do you compare modeled SWE against observed river discharge? These are very different parameters. Storage exerts a large control over how much snowmelt water is delivered to the stream network.

In that study end of season basin average SWE simulated by the PWBM was compared against discharge following snowmelt. In Arctic regions spring (or in general the 'freshet' period) discharge is largely controlled by the amount of snowpack water storage. In that study basin-averaged PWBM SWE prior to snowmelt explained a statistically significant fraction of interannual variability in spring (April – June) river discharge. We agree that storage potential plays an important role.

Lines 161-164: The authors either need to provide more information on how the model was parameterised and how it performs, or provide references to previous publications that have previously done this.

We cite four key papers in the Hydrological Modeling section. Lines 175-186. These are Rawlins et al. (2003); Rawlins et al. (2013); Yi et al. (2015); Yi et al. (2019). We also detail the new model updates in that section. Starting at line 187.

Lines 218-19: Can you provide more justification for why effective velocity was set to v= 0.175? This appears to be an important parameterisation of the model but there is very little justification given.

We selected the effective velocity based on the relatively flat topography of the North Slope. We find that the model is relatively insensitive to the choice of flow velocity in comparing with gauged data for the Kuparuk River. Indeed, applying the default flow velocity results in a bias in timing of peak discharge by -7.8 days early compared with gauge observations. In two additional simulations using a velocity 33% lower and 33% higher results in a bias of -5.4 and -9.0 days respectively. Many of the rivers in this region are shorter than the Kuparuk, so travel times are relatively short on the North Slope. It is no surprise that altering the flow velocity by 33% results in the timing of peak discharge shifting by only 1-2 days. The parametrization of flow velocity would have a much greater influence for long Arctic rivers like the Yukon, Mackenzie, and large Russian rivers. Accordingly we have added language at lines 295-299 with the result of sensitivity simulations.

Line 233: Are there any CALM sites or other field based observations from which the authors could compare their modeling results?

Simulated ALT is compared to estimates from a model developed at the Geophysical Institute. We previously described model validation for the sol thermal regime (Rawlins et al., 2013). Other recent studies using the PWBM (Yi et al., 2019) have compared estimates from the soil thermal model with observations. Point to grid cell comparisons for a few sparse locations should be viewed cautiously. We show that ALT calculated in the PWBM simulation with adjusted MERRA precipitation forcing closely matches the distribution simulated by the GIPL model, and that simulated ALT captures the expected spatial gradient across the region. Figure S2 and discussion starting at line 255.

Line 255: Why is only one basin used for validation?

Year-round discharge data at the coast is only available for the Kuparuk River. We have added a comparison with discharge for the Colville River for several months with observations. The data, however, are only available for the years 2002 onward, providing a nine-year climatology 2002-2010.

Line 263: Typo, “this occurs despite”

Word ‘occurs’ added.

Lines 267-268: Again, please display on daily timesteps and provide model performance evaluation.

The model is intrinsically daily time step. We feel that analysis of monthly runoff is sufficient for characterizing the hydrology at this time. Daily is simply expecting too much. See prior information in this review response.

Line 296: Please provide observational data to validate the modeled data.

The observational data for river discharge and SWE are provided freely to the research community. We have added detail of the SWE data. Line 123.

Line 309: Is surface runoff defined as overland flow?

Yes.

How are surface organics handled in the model?

Surface organics are parametrized using the Northern Circumpolar Soil Carbon Database (NCSCD). Lines 197-199 .

Many sites in the tundra have surface organics or peat layers where the porosity of near-surface soil is very close to 1, effectively eliminating overland flow due to the lack of resistance to flow exerted by the soil. In these situations would all runoff be subsurface? A better description of soil layers and modeling structure is needed to allow the reader to conceptualise the processes that are being explained.

Yes. The soil layers with high near-surface organic content have a poposity of 90%. This results in relatively high infiltration rates, and would, in most instances, lead to relatively higher amounts of subsurface runoff. Overland flow could still occur if surface (ponded) water is present and/or the infiltration capacity has been exceeded. Section 2.3 on the hydrological model is fairly detailed. Runoff occurs when water in a soil layer goes above field capacity. Line 172. The model is described in more detail in Rawlins et al. 2003, 2013 and Yi 2015.

Lines 361-363: Provide references.

Several references added.

Lines 362-363: “materials exports to coastal zones ”typo

Corrected.

Lines 371-372: Why not test this and include in the current model?

A suite of model upgrades are currently being designed, tested, and implemented. Incorporating new upgrades is not feasible for the current study. We look forward to describing upcoming model improvements in subsequent publications.

Lines 395-396: Which processes? The authors should be explicit about how hydrological processes are changing and cite field-based research to do so. For example, there have been quite a few relevant papers published from studies in northern Canada that are not referenced.

We appreciate the comment. Our manuscript is very explicit about how hydrological processes are changing, and we have cited field- and modeling-based research. We have modified the statement to indicate the changes in the Colville basin are greatest foothills regions. Line 473-474. We also added additional detail throughout the Summary and Discussion including in the paragraph starting at line 501. We now feel that the most relevant studies are cited.

**Review #2**

General Comments: This paper evaluates how discharge(surface/subsurface flow) and active layer thaw is changing across the North Slope of Alaska and NW Canada. It uses a detailed permafrost water balance model to simulate flow and examine changes in the active layer across 42 catchments in this continuous permafrost area. Overall the objectives of the paper are clearly outlined. Model performance is compared with measured runoff data, namely the Kuparak watershed. The authors' model was not able to capture large discharge peaks and time of simulated spring snowmelt runoff was 10 days earlier than observed estimates. Overall, the authors provide adequate explanation for model inconsistencies, and indicate that better performance may be tied to an improved understanding of lag effects (e.g. antecedent moisture conditions), landscape micro-topography (surface storage), soil type and soil organic content. They also demonstrate that large tracts of the North Slope area are thawing, which is leading to slightly higher cold season discharge, and earlier snowmelt ~ 4 days. They link their modelled and observed results to recent arctic discharge and groundwater flow studies occurring elsewhere (e.g. Middle Lena Basin) and biogeochemistry. Overall, this paper is interesting and furthers our understanding of runoff and ground thaw changes across the Alaskan North Slope and NW Canada. The paper could be improved by a model flow-chart and further details on model parameter choices (e.g.effective velocity) (please see below for further comments).

Specific Comments:

1)Line 28. Do you mean in 24 of 42 study basins? Also, it would be worthwhile to have a table of the 42 study basins describing basin areas, elevation range and locations (latitude/longitude). Perhaps, this site information could be placed into a Supplementary Table or an Appendix.

We have added "for" to the sentence. It now reads: "A significant increase in the proportion of subsurface runoff to total runoff is noted for the region and **for** 24 of 42 study basins, with the change most prevalent across the northern foothills of the Brooks Range."

2) Line 38. Can you add subsurface flow to the list of keywords.

Yes. Added.

3) Line 76. Do you mean increased hydrological connectivity instead of hydrological conductivity? If the ground thaws, then the flow of water further down in the active layer is usually much slower than it is in the near surface or when the active layer is frozen, and overland flow occurs.

Yes, although we believe an increase in conductivity would accompany the increase in connectivity. Word changed. Line 79.

4) Line 98. You can just put NW Canada.

Done.

5) Line 104. Just put NW Canada. Please take out extreme, and also just use NW, instead of northwest, since you used NW in Line 98.

Word ‘extreme’ removed.

6) Line 106. In your map, please indicate some major communities: Utqiakvik, Prudoe Bay(or Sagavanirktok) and perhaps a Canadian northern community too.

New map of domain now included as Figure 1. Major communities indicated. The hamlet of Aklavik, Canada is just south of the small river basin nearby.

7) Line 107. Again, it would be good to have a list of these 42 watersheds, particularly information on their catchment size, location of outlets and source for discharge information (e.g. USGS, Water Survey of Canada), etc.

We have added a table of the 42 river basins defined by the simulated topological river network. The table includes outlet coordinates, name where applicable, and basin area. Discharge information is used for the Kuparuk and Colville. There are no gauged data available for the small area in NW Canada. We reference USGS data source in the Data section. Lines 120-122.

8) Line 180. Could you clarify what you mean by ‘transient ponded surface evaporation’?

Sentence added to clarify: “Transient surface storage consists of water connected to the surface flow that is delayed in its transport to stream networks.” Line 215.

9) Lines 197-198. I don’t understand what you mean by .... ‘Following initial assessments we increased soil carbon amounts by 10% in areas of sandy soils....’ Was this based on model runs or on the research from Nicolsky et al.(2017). Please clarify-thank you!

The statement is based on initial model runs. During our assessments we concluded that the model parameterizations for soil carbon amounts and hydrological properties in the Brooks Range were inconsistent with our understanding of the region. We have modified the sentence: “Based on analysis of initial model simulations we increased soil carbon amounts by 10% in areas (24 grid cells) of sandy soils and reassigned the texture to loam, …” Line 209.

10) Lines 204-209. I don’t understand what you are doing in lines 204-209. Can you provide more details for adjusting evaporation and runoff functions?

We have modified the first three sentences of that paragraph to be clearer on our motivation. Paragraph begins at line 213.

11) Line 219. It is not clear why you set the effective velocity at 0.175. Can you provide additional justification here for this parameter?

We appreciate the comment and concern. The river flow routing routine is new. We addressed this in response to comment by reviewer 1. The model is relatively insensitive to specification of flow velocity. See statements in lines 292-299.

12) Lines 256-268. Interesting that simulated freshet leads observed freshet by 10 days, indicating that your snowmelt routine and routing are likely too fast. Does your snowmelt routine take into account a snowpack cold content, which can slow down melt progression? Along stream channels does your model account for the effects of channel snow or snow dams,which can pond meltwater and slow down runoff? Small terrestrial ponds can open up quickly too during snowmelt, and can retain much overland flow, especially if they have sufficient storage (low snow year, or antecedent storage

conditions). I do realize that you mentioned lag effects in the system but a 10 day spread in modelled versus simulated results appears to be on the high side.

We agree that the source of the error is likely a model snowpack that melts too rapidly. Given its length, travel time through the Kuparuk is too short to conclude that the river routing is too fast at the velocity we use. Our snowmelt routine is a function of air temperature and precipitation. We are working now on implementing a new snowmelt module that takes into account snowpack temperature. The PWBM contains no channel snow, but does account for the effects of snow damming, as described in Rawlins et al. (2003). We disagree that the magnitude of error is problematic, as our primary interest is in quantifying seasonal export of riverine constituents like dissolved organic carbon. We anticipate that new model updates will ameliorate the early bias. We have described the bias in a transparent way and feel strongly that daily accuracy is not required for a model used to quantify seasonal freshwater and constituent exports across this remote region that is lacking in measured data.

13) Line 296. Is cold season discharge simulated for the basins? It was not clear to me whether these data were modelled or measured. Low flows can have large uncertainties due to the ice cover, so how confident are you in these results?

Yes, here we are addressing simulated discharge. Word added at line 366. There are no measured data that will allow for comprehensive evaluations of simulated cold season discharge. We are very confident that the PWBM includes all key processes necessary to simulate the water cycle at spatial and temporal scales critical to understanding the nature of hydrological change across the region. Uncertainties are indeed larger for low flows.

14) Lines 342-343. I don’t have access to Figure S6. Could this supplementary figure be added to the paper?

It is our understanding that the supplemental section was made available for review and will be available to readers upon publication.

15) Lines 352-353. What is going on in the one basin where you see a large shift in maximum peak discharge?

The change in timing of maximum daily discharge for that basin is not much different from several others. It is simply the case that, for that one river, the change is statistically significant. Many of the 42 rivers show a peak discharge nearly one week earlier over the 30 years. The change does not achieve significance above the 95% level due to the high interannual variability. We have added a sentence to make this clearer. Line 425.

16) Line 365. I think that ‘Arctic’ should be arctic here.

Yes. Changed.

17) Line 370. Can you clarify what you mean by ‘insufficient surface storages in the model’? Do you mean pond storage, or depression storage arising from hummock/hollow micro-topography?

We mean the latter. Sentence modified to be more clear. Lines 446-449.

18) Lines 371-372. Yes, I agree. You need to improve your surface storage sub-routine, especially if you are losing near-surface ground ice, as your landscape micro-topography is probably evolving.

We agree. Modeling changes in micro-topography will require implementation and parameterization of a numerical model at finer spatial resolution and across smaller regions.

19) Lines 402-406. Can you clarify your statement about the role of permafrost and the link between your study and that of the Lena River. It wasn’t quite clear to me, even after I read the Gautier et al. (2018) paper. They appeared to indicate that the size of the spring freshet was more important in controlling the maximum and minimum ratio rather than an increase in fall groundwater flow.

We have reworked the sentence. Gautier et al. (2018) suggested that the change in ratio was mainly due to the increased minimum river base flow in winter. Also documented by Yang et al. (2002). Line 481-484.

20) Line 424. It should be ‘exert’

Corrected.

Technical Corrections:

1) Check over references. Some of the titles have all caps, others not. Some of the page numbers for recent journal articles should be double checked.

We checked all references against the published work. Reference title matches the title in the published paper.

2) Table 1. Figure S2 indicated in the Figure title is not available. I did not have access to it or it is missing.

It is in the supplemental section.

3) Table 2. You may as well list the details for all 42 catchments.

New Table S1 included.

4) Figure 1. Can you add the air temperature to Figure 1, and can you show the ratio of snow to rainfall in the bar diagram for precipitation.

Yes. Done. See revised Figure 2

5) Figure 4. Is this modelled discharge or observed discharge. Perhaps, clarify in the figure title-thank you!

Figure shows model simulated river discharge. Word ‘simulated’ has been added to figure title and caption.

6) A flow chart of your permafrost water balance model would be most helpful.

A schematic diagram of the PWBM was published in Rawlins et al. (2013). A flow chart would likely be simply input -> model -> outputs.

**Reviewer 3**

The paper aims at the analysis of baseline conditions and changes of hydrological elements at 42 catchments over the period 1981-2010. For this purpose, an updated version of the Pan-Arctic Water Balance Model (PWBM) was applied. The presented results indicate statistically significant increases in cold season discharge. A significant increase in the ratio of subsurface runoff to total runoff was found for 24 of 42 studied catchments. These changes correspond well to the increase of the active layer thickness due to higher air temperature and general climate warming.

The topic is potentially interesting for the hydrological society, especially the analyses of the non-stationarity of hydrologic processes in cold climate due to climate change.

However, I have many concerns and comments on the methodology that should be addressed. The most important is the lack of model validation. The presented results are mostly simulation-based and cannot be analysed without appropriate model validation. The results of validation for the Kuparuk catchment are not promising. I would not use this model for the assessment of changes in the timing of maximum flows. The error of maximum flows was estimated to 9 days while shifting in peak spring occur around 4.5 days earlier. The error is higher than the simulated changes.

Additional comparisons have been added. A new model validation section has been added. Line 253. We do not agree that validation for the Kuparuk catchment is not promising. Model simulated SWE exhibits a statistically significant correlation with measured SWE, and simulated runoff exhibits a statistically significant correlation with measured runoff (estimated via discharge). The error in runoff over the freshet period of May-June is a mere +0.3%. Yes, the error in timing of peak discharge is 8 days, nearly twice the report change in timing of maximum daily discharge for all watershed. There is uncertainty in that timing shift. That said, we believe the shift to earlier maximum discharge is being forced by spring warming that is approximately 5.4 F over the 30 year period examined. We are prepared to drop this aspect of the study. See also the responses to reviewer 1 and 2 for further information on model validation. Also the new statements and prior papers using PWBM cited at lines 175-186.

In my opinion, the model description is not sufficient. There is no information regarding solved equations, water balance, thermal balance.  Is the energy balance included in the model?  Is soil temperature modelled separately or is it included in the PWBM? There is no information regarding the model parameters (number of parameters, their meaning, how the model parameters were determined?  By optimisation?  Or just assumed?  There is also lack of information on applied optimisation method).  Some of the parameters were selected in a strange way without any explanation (for example changes in f parameter that is described in lines 207-209, the assumption of the effective velocity v=0.35m/s).  Are the values of this parameter constant for the entire domain? Why is evaporation reduced to 1/3 of the potential ET rate?

The PWBM has been described in detail in several earlier peer-reviewed publications. These include Rawlins et al. (2003), Rawlins et al. (2013), Yi et al. (2015), and Yi et al. (2019). The first three publications each contain an Appendix which details the model processes and parameterizations. It is through these prior efforts that we have built a legacy of model descriptions. The soil thermal model was described in detail in Appendix A of Rawlins et al. (2013). We have added a sentence at line pointing the interested reader to the 4 key publications.

The results are largely insensitive to specification of flow velocity. Sensitivity test described at line 296. The PWBM is best described as an intermediate complexity model. For this study two new submodels were designed, tested, and implemented, involving a surface water layer and river flow routing. Three new parameterization were implemented: evaporation from the surface layer, runoff from the surface layer, and effective river flow velocity. These three parameters were established in these new model runs, in part, based on visually comparing with river discharge data. We find that the model is relatively insensitive to the choice of flow velocity for the Kuparuk River. Indeed, applying the default flow velocity results in a bias in timing of peak discharge by -7.8 days early compared with gauge observations. In two additional simulations using a velocity 33% lower and 33% higher results in a bias of -5.4 and -9.0 days respectively. Many of the rivers in this region are shorter than the Kuparuk, so travel times are relatively short on the North Slope. It is no surprise that altering the flow velocity by 33% results in the timing of peak discharge shifting by only 1-2 days. The parametrization of flow velocity would have a much greater influence for long Arctic rivers like the Yukon, Mackenzie, and large Russian rivers. We are in the process of making additional improvements to the flow routing network and submodel. The evaporation rate of ⅓ of PET is set only for the ponded surface layer. Water in lakes and ponds evaporates at the PET rate. The value for surface ponding was chosen assuming the limiting effects of water sitting in local storage depressions. Lines 296 is the statement on the result of sensitivity simulations.

There is a lack of map and description of the study area. It is stated that 42 catchments are analysed, but only results for one or three catchments are presented. Are the results the same? Are there any differences in the results between catchments? How are these results summarised?

We have added a map of the study domain as new Figure 1. The domain is introduced beginning with the start of the paragraph at line 104. We have included a Table showing several defining elements of the 42 river basins of the simulated topological network. In the paper we described results for the three largest river basins which have some monitoring, and the full study regional. Results are not the same for all basins. We have characterized differences for the largest basins for select geophysical quantities, for example, Table 2 and Figure 6. We do not present summary results for all 42 watersheds and see no additional value in including analysis for smaller basins. The regional perspective, we feel, is more valuable. Runoff estimates along with the analyzed geophysical quantities will be made available to the research community for further analysis.

SWE simulations were evaluated using average values from observations collected at a 200x300 km domain. The PWBM was run at 25 km resolution. These are completely different scales. Large differences in SWE especially for 2004.

This concern would be valid if simulated SWE was compared against single ground-based SWE measurement. This is not the case. Ground-based SWE measurements were collected at multiple snow survey sites distributed across the entire Kuparuk River watershed so that snow measurements capture orographic effect from coastline to the mountains, Brooks Range. In this paper, SWE averaged from all snow survey sites in the Kuparuk River watershed was compared with the simulated SWE averaged over the same watershed. We clarified the compatibility of modeled/measured SWE in the text, see lines 122-126.

Why was a linear trend analysed? I suggest using a modified Mann-Kendall trend test for autocorrelated data for this purpose. The test should be applied separately for each catchment and then the results should be analysed I don't have any great advice for tidying up the manuscript, but basically I think it somehow needs to be streamlined,made easier to read and corrected. Some of the conclusions should be reconsidered,better highlighted and more concisely presented. The authors should be more clear about the meaning of statistical significance of their results and more careful when drawing conclusions from non-significant results. There are major errors or gaps in the paper but it could still become significant with major changes, revisions, and/or additional data.

In this study we evaluated time changes for end of season active-layer thickness, annual discharge, the fraction of subsurface runoff, cold season discharge, total terrestrial water storage (TWS), and its component storage amounts. For all but TWS, the trends are calculated from once-a-year values. We perform no statistical analysis on daily data. As described in Hirsh et al. "Statistical Treatment of Hydrologic Data" in Maidment (1993), while daily river discharge often exhibits auto-correlation, annual discharge does not. For the annual quantities free of autocorrelation we applied the standard Mann-Kendall non-parametric test to assess statistical significance through the associated p values and corrected Z values. The quantities comprising TWS have some memory, so we used the modified Mann-Kendall test for TWS and its component storages. Revised text at lines 244-252.

Maidment, D.R., 1993. *Handbook of hydrology* (Vol. 9780070, p. 397323). New York: McGraw-Hill.

# Changing Characteristics of Runoff and Freshwater Export From Watersheds Draining Northern Alaska

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## Abstract

The quantity and quality of river discharge in arctic regions is influenced by many processes including climate, watershed attributes and, increasingly, hydrological cycle intensification and permafrost thaw. We used a hydrological model to quantify baseline conditions and investigate the changing character of hydrological elements for Arctic watersheds between Point Barrow and just west of Mackenzie River over the period 1981–2010. ~~The region annually exports 28.1~~ A synthesis of measurements and model simulations shows that the region exports 31.9 km$^3$ yr$^{-1}$ of freshwater via river discharge, with ~~51.9% (14.6~~ 57.7% (18.4 km$^3$ yr$^{-1}$) coming collectively from the Colville, Kuparuk, and Sagavanirktok rivers. ~~Our results~~ The simulations point to significant ($p <$

0.05) increases (134–212% of average) in cold season discharge (CSD) for several large North Slope rivers including the Colville and Kuparuk, and for the region as a whole. A significant increase in the proportion of subsurface runoff to total runoff is noted for the region and for 24 of the 42 study basins, with the change most prevalent across the northern foothills of the Brooks Range. Relatively large increases in simulated active-layer thickness (ALT) suggest a physical connection between warming climate, permafrost degradation, and increasing subsurface flow to streams and rivers. A decline in terrestrial water storage (TWS) is attributed to losses in soil ice that outweigh gains in soil liquid water storage. Over the 30 yr period the timing of peak spring (freshet) discharge shifts earlier by 4.5 days, though the time trend is only marginally ($p = 0.1$) significant. These changing characteristics of Arctic rivers have important implications for water, carbon, and nutrient cycling in coastal environments.

KEYWORDS: Arctic; runoff; river discharge; permafrost; subsurface flow

# 1 Introduction

The arctic water cycle is central to a range of climatic processes and to the transfer of carbon, energy, and ~~a host of other constituents~~ other materials from the land mass to coastal waters of the Arctic Ocean. Freshwater export to the Arctic Ocean is high relative to the ocean's area (Shiklomanov et al., 2000), and dominated by river discharge (Serreze et al., 2006), which serves as a conveyance for carbon and heat across the land-ocean boundary. Syntheses of data and models have advanced understanding of key linkages and feedbacks in the Arctic system (Francis et al., 2009), mean freshwater budgets across the land, atmosphere and ocean domains (Serreze et al., 2006), and time trends in observations and model estimates over the latter decades of the 20th century (Rawlins et al., 2010).

A warming climate is expected to lead to intensification of the hydrological cycle, including increases in net precipitation (P) at high latitudes~~. Evidence pointing to Arctic hydrological cycle~~, and evidence of broad-scale intensification is emerging (Peterson et al., 2002, 2006; Rawlins et al., 2010; Zhang et al., 2013; Bring et al., 2016). A more vigorous water cycle is related ~~both to~~ in part to both the amount of moisture air can hold and changes in atmospheric dynamics. Shorter ice duration on lakes and longer seasons for evaporation are also manifestations of warming on the Arctic hydrological cycle. Much of the increase in net P is expected to occur during winter (Kattsov et al., 2007), potentially through intensified local surface evaporation driven by retreating winter sea ice, and enhanced moisture inflow from lower latitudes (Zhang et al., 2013; Bintanja and Selten, 2014). An increase in river discharge from

Eurasia to the Arctic Ocean was noted in simulations with the HadCM3 general circulation model (Wu et al., 2005), illustrating the potential for increased winter net P to influence freshwater export. Positive trends in column-integrated precipitable water over the region north of 70°N, linked to positive anomalies in air and sea surface temperature and negative anomalies in end-of-summer sea ice extent (Serreze et al., 2012), support the future model projections. Rivers form a primary conduit for transferring terrestrial materials to the coastal ocean, and these materials exert a strong influence on marine ecosystems and carbon processing.

Permafrost warming and degradation has been observed over parts of Alaska, Russia, and Canada (Brown and Romanovsky, 2008; Romanovsky et al., 2010; Smith et al., 2010). In one study permafrost area is projected to decrease by more than 40%, assuming climate stablization at 2°C above pre-industrial (Chadburn et al., 2017). Warming and permafrost degradation is expected to cause a shift in arctic environments from a surface water-dominated system to a groundwater-dominated system (Frey and McClelland, 2009; Bring et al., 2016). There is increasing evidence of impacts of permafrost degradation on biogeochemical cycles on land and in aquatic systems. Recent reported increases in baseflow in arctic rivers are suggestive of increased hydrological ~~conductivity~~ connectivity due to permafrost thaw ~~(Walvoord and Striegl, 2007; Bense et al., 2009; St. Jacques and Sauchyn, 2009)~~(Walvoord and Strieg Groundwater processes have a dominant role in controlling carbon export from the land to streams in permafrost terrain (Frey and McClelland, 2009; Neilson et al., 2018). In areas where much of the landscape is defined by the absence of permafrost, runoff generation processes can be much different from areas where permafrost is nearly continuous. Dissolved organic matter (DOM) transported by Arctic rivers contain geochemical signatures of the watersheds they drain, reflecting their unique characteristics (Kaiser et al., 2017). Changes in landscape characteristics and water flow paths as a result of climatic warming and associated active layer thickening have the potential to alter aquatic and riverine biogeochemical fluxes (Frey and McClelland, 2009; Wrona et al., 2016; Wickland et al., 2018). Increased flow through mineral soils has been linked to decreases in DOC export from the Yukon River over recent decades (Striegl et al., 2005). In contrast, areas with deep peat deposits that experience thaw may see increasing DOC mobilization and export as permafrost degrades (Frey and Smith, 2005).

This study presents baseline freshwater flux estimates and examines elements of the hydrological cycle across the North Slope over the period 1981–2010. We use measured data to assess model performance and combine with the simulated estimates to quantify freshwater export from the region. We then ~~leverage the modeling framework to investigate signs of change~~ use the data and model simulations to investigate time changes in runoff and river discharge, the proportion of groundwater runoff, terrestrial water storage, and the timing of peak daily discharge. Salient results in the context of arctic change and directions for future research are discussed.

# 2 Study Area, Data and Modeling

~~Our~~ The study focuses on the North Slope of Alaska and ~~far~~ NW Canada, partitioned by the region's river basins that drain to the Beaufort Sea ~~and Arctic Ocean. In the text,~~ (Figure 1). Hereafter we refer to ~~the entire study area~~ this region as the "North Slope". ~~Model input and output fields are resolved at a daily time step.~~ The grid is based on the Northern Hemisphere EASE-Grid (Brodzik and Knowles, 2002), with a horizontal resolution of 25 km for each grid cell. The ~~area draining the North Slope~~ model domain contains 312 grid cells (total area = 196,060 km$^2$) ~~across~~ that define the North Slope drainage of northern Alaska and ~~extreme northwest~~ NW Canada. It is defined by the ~~watersheds~~ drainage basins of rivers (42 ~~in total) of rivers~~ total, Table S1) with an outlet along the coast from just west of the Mackenzie River to Utqiakvik (formerly Barrow) to the west. Hydrologic modeling was performed for the North Slope domain encompassing the 42 watersheds. Many North Slope rivers are oriented roughly north-south~~. The study area~~, and the region is underlain by continuous permafrost, approximately 250–300 m thick in the Brooks Range and, locally, up to nearly 400 m thick near the coast (Jorgenson et al., 2008).

## 2.1 Observational data

Observational data used in this study include time series of daily river discharge, end-of-winter snow water equivalent (SWE), and seasonal maximum active-layer thickness (ALT). Historical river discharge data was retrieved from the USGS for the Kuparuk River (~~station~~ http://waterdata.usgs.gov/nwis/uv?15896000) ~~was retrieved from the USGS at http~~and Colville River (https://waterdata.usgs.gov/ak/nwis/uv~~?15896000.~~/?site_no=15875000). Model simulated SWE is evaluated against average end-of-winter SWE from measurements across the Kuparuk River watershed. The measurements from 2000 to 2011 were taken at multiple locations distributed from the Brooks Range to the Beaufort Sea coast to better capture macro-scale SWE variability (Stuefer et al., 2013).

Simulated ALT from the PWBM (section 2.3) is compared with estimates from a ~~related~~ high-resolution 1-D heat conduction model (developed by the University of Alaska's Geophysical Institute Permafrost Laboratory, hereafter referred to as GIPL) that incorporated data on ecosystem type and was validated against measured CALM network ALTs (Nicolsky et al., 2017). ~~Model simulated SWE is evaluated against average values from 12 years of SWE observations collected across a 200×300 km domain that includes the Kuparuk River watershed from the Brooks Range to the Beaufort Sea coast (Stuefer et al., 2013).~~

## 2.2 Reanalysis data

Gridded fields of daily surface (2 m) air temperature, precipitation (P), and wind speed are used as model forcings. Obtaining accurate temporally varying P estimates at daily resolution is particular challenging in arctic environments. Gauge undercatch of solid P is common, the gauge network is sparse and the number of stations at higher elevation is insufficient (Yang et al., 1998, 2005; Kane and Stuefer, 2015). In this study model meteorological forcings are drawn from the Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. (2011)). In a recent intercomparison of P estimates over the Arctic Ocean and its peripheral seas, three reanalyses— ERA-Interim (Dee et al. (2011)), MERRA, and NCEP R2 (Kistler et al. (2001))— produce realistic magnitudes and temporal agreement with observed P events, while two products (MERRA, version 2 (MERRA-2), and CFSR) show large, implausible magnitudes in P events (Boisvert et al., 2018). Given a modest low bias in monthly P across the North Slope in MERRA, we derived a new bias corrected daily P time series by scaling the MERRA values by a factor defined using monthly long-term mean P (1981–2010) from MERRA, ERA-Interim, and a data set that blends simulations from ERA-Interim and the Polar WRF (Cai et al., 2018). Those three data sets exhibit a similar spatial pattern in annual P across the region. Annual P generally ranges from as low as 200 mm $\text{yr}^{-1}$ near the coast to over 400 mm $\text{yr}^{-1}$ over the foothills of the Brooks Range. At each grid cell, the offset ratio was defined as average P from the 3 data sets divided by the MERRA P amount. The derived daily P (hereafter MERRA*) was then calculated as the daily MERRA P amount multiplied by the offset ratio.

## 2.3 Hydrological modeling

The regional hydrology is characterized by water fluxes and storages expressed in simulations using a spatially-distributed numerical model. Referenced previously as the Pan-Arctic Water Balance Model (PWBM), the numerical framework encompasses all major elements of the water cycle, including snow storage, sublimation, transpiration, and surface evaporation (Rawlins et al., 2003, 2013). ~~It is run~~ Model input and output fields are resolved at a daily time step. The simulations are commonly performed at an implicit daily time step~~and is~~, typically forced with meteorological data. The PWBM has been used to investigate causes behind the record Eurasian discharge in 2007 (Rawlins et al., 2009); to corroborate remote sensing estimates of surface water dynamics (Schroeder et al., 2010); and to quantify present and future water cycle changes in the area of Nome, Alaska (Clilverd et al., 2011). In a comparison against observed river discharge, PWBM-simulated SWE fields compared favorably (Rawlins et al., 2007). Soil temperature ~~dynamics are simulated through a~~ are simulated dynamically are through an embedded 1-D nonlinear heat conduction ~~model~~ sub-model with phase change (Rawlins et al., 2013; Nicolsky et al., 2017). PWBM includes a multi-layer snow model that accounts for wind compaction, change in density due to fresh snowfall, and depth hoar development with time. Runoff is the sum total of surface (overland) and subsurface flow each day. Subsurface runoff occurs when the amount of water in a soil layer exceeds field capacity.

The model is well suited for application across the North Slope region. Active-layer thickness (ALT) simulated using the PWBM ~~soil submodel~~ was found to be more similar to in situ observations and airborne radar retrievals in continuous permafrost areas than in lower permafrost probability areas (Yi et al., 2018). The influence of snow cover and soil thermal dynamics on the seasonal and spatial variability in soil CO$_2$ respiration ~~was~~ has been quantified by coupling PWBM to a dynamic soil carbon model (Yi et al., 2013, 2015). A key model attribute is its ability to dynamically simulate the direct influence the snowpack exerts on soil temperature (Yi et al., 2019), with deeper snowpacks promoting warmer soils and associated effects, such as enhancement of soil decomposition and respiration from deeper ($\geq 0.5$ m) soil layers (Yi et al., 2015). Detailed descriptions of the PWBM can be found in Rawlins et al. (2003, 2013); Yi et al. (2015, 2019) and Appendices within.

In this study we applied an updated version of the model, and given its detailed representation of soil freeze-thaw processes, rename it the "Permafrost Water Balance Model" (hereafter PWBM v3). ~~Modifications~~ Recent modifications involved the incorporation of new data and parametrizations for surface fractional open water ($fw$) cover, soil carbon content, and transient ponded surface evaporation and runoff. Updates to the spatial estimates of $f_w$ were ~~taken~~ drawn from a product derived from brightness temperature ($T_b$) retrievals from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) (Du et al., 2017) to parameterize the grid cell fraction of open water (annual average) across the model domain. Properties of near surface organic-rich soils strongly control hydrological and thermal dynamics in the seasonally thawed active layer. We used soil organic carbon (SOC) estimates from version 2.2 of the Northern Circumpolar Soil Carbon Database (NCSCD), a digital soil map database linked to extensive field-based SOC storage data (Hugelius et al., 2014). The database contains SOC stocks for the upper 0–1 m and for deeper soils from 1–2 and 2–3 m depth. In the updated PWBM v3 the sum total of SOC in the upper 3 m was used to derive the organic layer thickness as described in Rawlins et al. (2013). The resulting spatially varying parameterizations of soil carbon profiles (% of volume) with depth over the domain (Figure S1~~b~~a) influence soil thermal properties and hydrological storages and fluxes. ~~The maps show broad agreement~~ Broad agreement exists in the spatial pattern of the independent soil ~~texture and soil carbon datasets~~ carbon and soil texture datasets (Figure S1a,b). Sandy soils and soil carbon thicknesses under 20 cm occur over the Brooks Range, and relatively higher soil carbon thicknesses and loam soils are present across the tundra to the north. ~~Following initial assessments~~ Based on analysis of initial model simulations we increased soil carbon amounts by 10% in areas (24 grid cells) of sandy soils and reassigned ~~24 grid cells~~ the texture to loam, ~~to be~~ making the parameterizations more consistent with soil textures inferred from ~~the~~ high-resolution ALT mapping ~~via~~ using the GIPL model that incorporated data on ecosystem type (Nicolsky et al., 2017).

Model calibration was performed to adapt the model and optimize its performances in simulating the water cycle across the study domain, and involved the surface transient storage pool and river flow velocity. Transient surface storage consists of water connected to the surface flow that is delayed in its transport to stream networks. Parameters controlling evaporation and runoff fluxes from ~~transient surface storages~~ surface storage were modified to better account for delays in water reaching stream channels. Defining ~~$E_i$, $R_i$, and $S_i$~~ $\mathrm{E_i}$, $\mathrm{R_i}$, and $\mathrm{S_i}$ to represent evaporation (or evapotranspiration)(mm day$^{-1}$), runoff (mm day$^{-1}$, and storage (mm) in soil layer ~~$i$~~i, respectively, then ~~$E_0$, $R_0$, $S_0$~~ $\mathrm{E_0}$, $\mathrm{R_0}$, $\mathrm{S_0}$ are evaporation, runoff, and storage from the model surface layer, ~~$R_0 = S_0 * f$~~ $\mathrm{R_0 = S_0 * f}$ (mm day$^{-1}$). In the updated model f = 0.40, reduced from the prior value of 0.75. Evaporation from surface storage is ~~$E_0 = S_0 * g$~~ $\mathrm{E_0 = S_0 * g}$, with g now reduced to 1/3 of the potential ET rate.

Model estimated runoff routed through a simulated topological network (STN) (Vörösmarty et al., 2000) is expressed as river discharge (volume flux) at the coastal outlets of 42 individual watersheds draining from Point Barrow to just west of the Mackenzie River delta. A simple linear routing model is used given the relatively short travel times through the North Slope basins. Water transferred to the downstream grid ~~(or ocean/lagoon) is~~ or exported off the coast is

$$\underline{Q_{out} = \frac{v}{d}S}\mathrm{Q_{out}} = \frac{\mathrm{v}}{\mathrm{d}}\mathrm{S} \tag{1}$$

where ~~$Q_{out}$~~ $\mathrm{Q_{out}}$ ($\mathrm{m^3\ s^{-1}}$) is flow downstream, ~~$v$~~ v is flow velocity ($\mathrm{m\ s^{-1}}$), ~~$d$~~ d is the distance between grid cells (m), and $S$ is volume of river water ($\mathrm{m^3}$). Miller et al. (1994) suggested a global average of ~~$v$~~ v = 0.35 $\mathrm{m\ s^{-1}}$. Given the relatively flat topography over much of the domain we set effective velocity at ~~$v$~~ v = 0.175. Hereafter R represents runoff expressed in unit depth, and Q represents river discharge volume flow estimated through the routing model.

The ~~model~~ PWBM is run in a 50 year spinup over year 1980 prior to the transient time series simulation to stabilize soil temperature and water storage pools. This spinup is followed by a 30 year transient simulation over the period 1981–2010, the focus of our analysis.

~~Statistical significance of a time trend in runoff or river discharge is assessed~~ Assessment of several model simulated quantities is made using average error and correlation. Model evaluation metrics based on squared values like the root mean square error (RMSE) are known to be biased and highly sensitive to outliers (Willmott and Matsuura, 20 Statistical significance is calculated using the Mann-Kendall test statistic (Hamed and Rao, 1998; Yue et al., 2002), with a 95% confidence level ($p < 0.05$) designated as statistically significant. ~~A~~ Time changes are estimated with a General Linear Model (GLM)~~is assumed for other analyzed quantities~~. We apply the modified Mann-Kendall test (Hamed and Rao, 1998) for terrestrial water storage (TWS) and its component storages of snow (water equivalent), soil liquid water and ice amounts. A one or a two-sided test is applied depending on whether the direction of change is assumed. For example, we posit null hypotheses that the region is experiencing increasing cold season discharge as a result of ALT increase. ~~Percent change over time is estimated using the GLM linear least squares slope and the climatological average for the time series examined.~~

# 3 ~~Results~~Model Validation

## 3.1 Active layer thickness

Simulated maximum seasonal ALT derived from daily soil temperatures in the updated PWBM v3 model ~~run using the MERRA~~ simulation with meteorological forcing from MERRA reanalysis (bias corrected MERRA* P) ~~display~~ is evaluated alongside ALT predicted from the GIPL model. Area averaged ALT from PWBM and GIPL is 53.5 and 55.2 cm respectively, a difference of ∼3% (Figure S2,Table 1), and smallest difference among average ALT derived from soil temperatures in simulations using alternate meteorological forcings. Simulated ALT exhibits the expected north-south gradient which reflects the gradient in summer (and annual) air temperature

~~. The pattern is also evident in ALT predicted from the GIPL , with agreement~~ (Figure S3). Agreement in ALT between PWBM (MERRA*) and GIPL is strongest in coastal areas. The ~~fields differ~~ estimates differ most near the center of the domain where the PWBM produces relatively ~~lower~~ smaller ALT compared to GIPL. ~~Area averaged ALT from PWBM and GIPL is 53.5 and 55.2 cm respectively, a difference of ~3% (Table 1).~~ The differences increase toward the extremes of each field, pointing to ~~larger~~ higher spatial variability in the PWBM simulations (Figure S2). ALT from simulations with the default MERRA P forcing are shallower and less in agreement with the GIPL data.

## 3.2 Snow water equivalent

~~Within the Kuparuk~~ In the Kuparuk River basin maximum end of season SWE typically occurs near the end of April. ~~Model simulated (PWBM v3)~~ Simulated end of season SWE each year is calculated as the average of daily values from April 24 to May 7, also averaged across all basin ~~grids. The model~~ grid cells. Average simulated SWE largely tracks the interannual variations in measured end of season SWE over the period 2000–2010, with an average difference of 5.3 mm or 4.8% of the average (109.7 mm) from the field measurements (Figure S4). The Pearson correlation ~~efficient~~ coefficient is $r = 0.78$, with the relationship significant at $p < 0.01$ (Figure S5).

## 3.3 Runoff and river discharge

### 3.3.1 Spring freshet

Modeled ~~spring freshet~~ runoff (R) from the simulation forced with MERRA* is evaluated against observed R for the ~~Kuparuk River watershed~~Colville and Kuparuk River watersheds. USGS measurements for the Kuparuk River at Deadhorse over the period 1981–2010 show that an average of 98.3 mm of runoff (R) is exported as discharge during the spring freshet, which we calculate as R occurring from day of year (DOY) 100 to ~~180. R is the unit depth of discharge over a given time interval, and distributed over a contributing watershed. Modeled freshet R calculated from the simulation forced with MERRA* leads the observed freshet R by approximately 10 days. This despite a relatively slow model river flow velocity ($v = 0.175$ m$^3$ s$^{-1}$~~180 (Figure 2, 3b). Simulated R over the freshet period ~~is~~ totals 98.0 mm. Simulated May R exceeds observed R by 29 mm month$^{-1}$, while simulated June R is 29 mm month$^{-1}$ lower than observed R~~(Figure 2)~~, resulting in the relatively small error (percent difference +0.3%) for total R over the freshet period. Simulated R closely tracks observed R in other months of the year with flow (Figure 2). For the Colville River, the available data beginning in late May show that the total volume simulated over the spring freshet is well captured, with average error of 10% (Figure 3a). Simulated R is underestimated in summer. The timing of simulated maximum daily Q closely matches the timing based on the measured data (Figure 3a). For the Kuparuk River simulated discharge leads observed discharge by approximately one week ($-7.8$ days, Figure 3b). For this region the flow routing sub-model is relatively insensitive to the specified flow velocity. Two sensitivity simulations using a velocity 33% lower and 33% higher than the default velocity ($v = 0.175$ m$^3$ s$^{-1}$) resulted in errors of $-5.4$ and $-9.0$ days respectively. Many of the rivers in this region are shorter than the Kuparuk, so travel times are relatively brief.

### 3.3.2 ~~Annual runoff and freshwater export~~

### 3.3.2 Annual runoff

~~Annual total P over the Kuparuk Basin ranges from 182 mm yr$^{-1}$ (2007)to 433 mm yr$^{-1}$ (2003)with no significant trend over the 30 year period (Figure 4). For~~ For the Kuparuk River annual total R as the long-term (30 yr) average from USGS observations and from the model simulation ~~are~~ is 144 and 134 mm yr$^{-1}$, respectively (percent difference = $-6.8$%) ~~. There is no significant trend in observed or simulated annual R over the 30 yr period. Simulated annual R~~ (Figure 4). Annual R from the simulation is correlated with observed annual R (Pearson correlation $r = 0.74$, $p < 0.001$), with average error of $+3.1$ mm yr$^{-1}$ (Figure S6). Observed R varies from 75–238 mm yr$^{-1}$, while simulated R is more conservative, extending over a range from 90–200 mm yr$^{-1}$. In other words, the model tends to overestimate R in years ~~with low annual flow, and vice versa~~when observations are high and underestimate R in years with low observed flow. For measured R partitioned at: $R < 100$ mm yr$^{-1}$, $100 \leq R \leq 200$ mm yr$^{-1}$, and $R > 200$ mm yr$^{-1}$, average errors are $+24.5$, $-1.8$, and $-52.2$ mm yr$^{-1}$, respectively. It is notable that in both 1996 and 2003 ~~,~~ annual R is higher in the year following a peak (within a several year span) in annual P. This lag highlights the role that antecedent storage plays in the region's river discharge regimes, and is consistent with previous research (Bowling et al., 2003; Stuefer et al., 2017).

# 4 Baseline Hydrology and Assessment of Changes

## 4.1 Annual precipitation and river discharge

For the period 1981–2010 annual total P averaged across the North Slope drainage basin ranged from 195 mm yr$^{-1}$ (1990) to 383 mm yr$^{-1}$ (2003) based on the adjusted MERRA* P data. Annual total P over the Kuparuk Basin varied from 182 mm yr$^{-1}$ (2007) to 433 mm yr$^{-1}$ (2003) (Figure 4). There is no significant trend in observed or simulated annual P or R for the Kuparuk (Figure 4) or any other river over the 30 yr period. Much higher annual runoff has been documented for the Kuparuk River in 2013, 2014, and 2015 (Stuefer et al., 2017). The spatial pattern in annual R (Figure 5a) reflects a similar gradient expressed in annual P from the coast southward into the Brooks Range, as R in this region is largely controlled by ~~P and~~ snow accumulation variations~~across the region.~~. Annual R averages over 250 mm yr$^{-1}$ across parts of the Brooks Range, while coastal areas average under ~~50~~ 100 mm yr$^{-1}$.

~~In the modeling framework simulated~~ Simulated R is routed ~~along the gridded river network~~ through the STN and expressed as a volume flux of river discharge (Q) at the Beaufort Sea coast. ~~For the period~~ There is a notable absence of routine monitoring of Q at river outlets near the coast. The Colville, Kuparuk, and Sagavanirktok Rivers are the three largest gauged North Slope rivers and occupy 46.2% of the study domain. Measurements for the Kuparuk River at Deadhorse are year round since the 1970s and capture flow from most of the basin. Data for the Colville at Umiat are available from late May until early October since 2002, but Q from just 56% of the full basin area flows past the gauge location. Data for the Sagavanirktok at Pump Station 3 are available from June through September since 1995. This gauge site is located far from the coast and captures Q from only 30% of the basin. Given these constraints we estimate baseline Q exports using the observed data for the Kuparuk River, a composite of measured data and model simulation for subbasins of the Colville, and simulated Q for the remainder of the study domain.

Annual Q (1981–2010~~, annual~~) for the Kuparuk River based on the USGS observations is 1.4 km$^3$ yr$^{-1}$ (144 mm yr$^{-1}$) (Table 2). The model simulated Q of 1.3 km$^3$ yr$^{-1}$ closely aligns with the observations and matches the 1.3 km$^3$ yr$^{-1}$ for 2000–2007 reported by McClelland et al. (2014) based on model simulations using Catchment Based Land Surface Model (CLSM). We leverage the measured data for the Colville River at Umiat (36,447 km$^2$) to estimate total Q for the ~~Colville~~entire (60,~~Kuparuk, and Sagavanirktok rivers combined averages 14.57~~ 095 km$^2$) Colville River basin. A data-model composite for the subbasin defined by the gauge at Umiat (area = 36,447 km$^2$) is calculated from the daily averages using measured Q when available (DOY 147 to 275) and simulated Q for the remainder of the year (Figure 3a). This gives a total Q of 9.2 km$^3$ yr$^{-1}$ (251 mm yr$^{-1}$). For the ungauged section of the basin (27,648 km$^2$) we bias adjust simulated monthly 2002–2010 R in months July, August and September assuming the ratio of simulated to observed at Umiat applies to the lower subbasin. This scaling for the ungaged subbasin produces 4.8 km$^3$ yr$^{-1}$, and combined with the discharge volume for the Umiat subbasin of 9.2 km$^3$ yr$^{-1}$ gives 14.0 km$^3$ yr$^{-1}$ for the full basin (Table 2). This estimate compares favorably to the 16 km$^3$ yr$^{-1}$ described by Arnborg et al. (1966) based on measurements in 1962, and is lower than the 19.7 km$^3$ yr$^{-1}$ (2000–2007) from McClelland et al. (2014). PWBM simulated Q (1981–2010) for the Sagavanirktok of 3.0 km$^3$ yr$^{-1}$ is bracketed by the 1.6 km$^3$ yr$^{-1}$ for 2000–2007 estimated by McClelland et al. (2014) and the 6.5 km$^3$ yr$^{-1}$ for 1971–2001 estimated by Rember and Trefry (2004) using USGS data. Our composite estimate for the Colville (14.0 km$^3$ yr$^{-1}$), measured Q for the Kuparuk (1.4 km$^3$ yr$^{-1}$) and modeled Q for the Sagavanirktok (3.0 km$^3$ yr$^{-1}$) totals 18.4 km$^3$ yr$^{-1}$ for the three rivers combined, which is ~~51.9% of the~~ 57.7% of North Slope domain total annual Q of ~~28.10~~ 31.9 km$^3$ yr$^{-1}$ (Table 2). ~~Those 3 watersheds occupy 46.2% of the North Slope study domain.~~

### 4.1.1 ~~Cold season discharge (CSD)~~

## 4.2 Cold season discharge (CSD)

Cold season (Nov–Apr) discharge (CSD) from the region simulated over the period 1981–2010 (0.116 km$^3$ season$^{-1}$) is 0.4% of annual total Q, and between 0.2–0.3% for each of the Colville, Kuparuk, and Sagavanirktok rivers. In this region nearly all of the CSD occurs during the first half of winter, namely November and December. CSD for the entire North Slope basin, and both the Colville and Kuparuk rivers, increased significantly (Mann-Kendall test, $p < 0.05$, Table 2, Figure 6). The CSD increase from the Colville is 215% of the long-term average. For the North Slope basin as a whole CSD increased 134% of the long-term average. Increasing CSD is noted for 9.0% of the North Slope domain, and 28.4% of the Colville basin, primarily in headwater catchments of the foothills of the Brooks Range (Figure 5b). In total the affected terrain covers 88,601 km$^2$ or 45% of the North Slope drainage.

## 4.3 Fraction of subsurface runoff

We examine variations in modeled surface and subsurface R through the year to better understand how warming is altering the hydrological flows. For the region as a whole the fraction of subsurface runoff to total runoff (hereafter ($F_{sub}$) increased 4.4% ($p < 0.01$), a 31% change relative to the 30 yr average of 14%. Both the Colville and Sagavanirktok rivers show statistically significant ($p < 0.05$) increases in $F_{sub}$, as do 20 of the 40 remaining basins. Significant increases are noted during several months, most widespread in September (58 of 312 ~~grids or~~ grid cells, 18.6% of ~~region~~domain) (Figure 7). Conversely, July shows a decrease in $F_{sub}$, although over less total area (5.4% of domain). For June and September the $F_{sub}$ increases average 34.8 and 40.2% respectively for the total change over the period. For July the average is $-38.3\%$, with 17 grids showing ~~an increase and two a decrease~~ a decrease and two an increase. At the annual time scale the increase in $F_{sub}$ is significant ~~($p < 0.05$)~~ for 24.7% of the study domain, most notably across the northern foothills of the Brooks Range from the western part of the region (Colville basin) eastward and toward the coast (Figure 8). $F_{sub}$ is consistently 100% of total runoff after October. Areas with increasing $F_{sub}$ are co-located with the areas experiencing increasing CSD.

Increasing $F_{sub}$ is noted in areas with a significant increase in active-layer thickness (ALT), primarily across parts of the northern foothills of the Brooks Range and the smaller basins near 140°W longitude (Figure 9). Statistically significant increases in ALT have been widespread, noted across two thirds (66.7%) of the region. The simulation shows that one fifth ~~of the region~~ (20.2%) of the region experienced a significant increase in both $F_{sub}$ and ALT ($p < 0.05$, Table 3). A fraction of the foothills region (5.1% of domain) is characterized by a positive trend in $F_{sub}$ only. ~~Statistically significant increases in ALT are widespread (66.7%).~~ The ALT trend average for grid cells with a significant increase in $F_{sub}$ only, a significant increase in ALT only, and a significant increase in both are 0.17, 0.75, and 1.00 cm yr$^{-1}$, respectively ~~. The relatively high~~ (Figure 10, Table 3). These relatively large ALT increases in areas of significant $F_{sub}$ increase indicate a connection between ~~increased~~ enhanced permafrost thaw and subsurface water flow in those areas~~(Figure 10, Table 3)~~.

## 4.4 Terrestrial water storage

Terrestrial water storage (TWS) over a given time interval is defined by the total amount of water stored in snow, soil liquid water, and soil ice as estimated by the model simulation. Over the 1981–2010 period annual average TWS (all 312 domain grids) exhibits a negative trend of approximately $-2$ mm yr$^{-1}$ ($p < 0.001$, Figure 11). Declines in annual minimum ($-1.7$ mm yr$^{-1}$) and maximum TWS ($-2.3$ mm yr$^{-1}$) are also significant. Among the component storages there is no significant change in ~~snow storage, an increase in minimum soil water amounts, and a decrease~~ SWE over the 30 year period (Figure S7). Increases in regionally averaged maximum and minimum soil liquid water, and decreases in soil ice ~~(Figure S7~~amounts, are significant ($p < 0.01$, modified Mann-Kendall test). The $-2$ mm yr$^{-1}$ decrease in TWS reflects a decrease in soil ice storage of $-2.5$ mm yr$^{-1}$, a ~~(insignificant) decrease in snow~~ decline in SWE of $-0.16$ mm yr$^{-1}$, and an increase in soil water storage of 0.61 mm yr$^{-1}$. ~~In addition to the annual averages, significant increases (decreases) in soil water (ice) annual minimum and maximum amounts are also noted.~~

### 4.5 Timing of maximum daily discharge

Warming and associated changes in snowmelt have the potential to cause shifts in the timing of peak discharge (Q) during the spring freshet period. Maximum spring discharge is determined from the daily model simulated and routed Q for each of the 42 North Slope ~~river basins~~domain rivers. In the ~~model~~ simulation only one of the 42 basins exhibits a significant shift to earlier maximum daily Q. None show a significant shift to later maximum Q. While many rivers show simulated peak discharge shifting nearly one week earlier over the 30 yr period, high interannual variability in annual Q renders the changes insignificant at the 95% level. The average date of maximum daily Q across the 42 basin advanced by approximately 4.5 days (Figure S8), though the change is ~~not statistically~~ only marginally significant ($p = 0.1$). Maximum daily Q from the region in recent years occurs near DOY 150 (end of May), though this estimate is potentially biased ~~8–10 days early~~ based on the comparison of simulated ~~runoff with measurements~~ and observed runoff for the Kuparuk River (subsection 3.3).

## 5 Summary and Discussion

Recent studies have investigated how hydrological cycle intensification and permafrost thaw may alter terrestrial hydrological fluxes and, in turn, materials ~~exports~~ export to coastal zones (Walvoord and Striegl, 2007; Frey and McClelland, 2009; Rawlins et al., 2010;
Changes unfolding across high latitude watersheds have the potential to significantly alter water, carbon, and other constituent fluxes, with implications for nearshore ~~Arctic~~ arctic biogeochemical and ecological processes.

~~Simulated runoff from PWBM v3 shows peak~~ Our synthesis of measured data and model simulations reveals that approximately 32 km$^3$ yr$^{-1}$ of freshwater is exported by the region's rivers, with 57.7% of the total originating from the Colville, Kuparuk, and Sagavanirktok Rivers. Simulated runoff for the Kuparuk River shows maximum daily spring discharge that ~~is systematically 8–10~~ exhibits a systematic bias of approximately 8 days early relative to gauge data. ~~This bias~~ Timing is well estimated for the Colville River. The timing bias for the Kuparuk is unrelated to the specification of river flow velocity in the ~~PWBM~~ routing scheme, and ~~more~~ likely due to a combination of errors in air temperature forcing or modeled snowmelt processes (warm bias) that lead to early snowpack thaw, and/or insufficient surface storages in the ~~mode which would~~ model which serve to delay the transfer of water to stream networks. Simulated R timing may improve by better accounting for these ~~delays~~ lags in snowmelt runoff. Future studies should investigate how dynamic surface inundation data ~~being produced~~ obtained from microwave and radar remote sensing (Schroeder et al., 2010; Du et al., 2016) can be used to constrain surface water storage, its partitioning to runoff and evaporation, and flow direction in areas of low topographic relief. The lag in ~~runoff~~ annual runoff for the Kuparuk River in 1996 and 2003 highlight how precipitation and antecedent storage conditions can influence the following year's runoff (Bowling et al., 2003; Stuefer et al., 2017).

The quantity and quality of freshwater export is expected to change significantly as the Arctic hydrological cycle intensifies and the system transitions toward increasing groundwater water flows (Frey et al., 2003; Frey and McClelland, 2009). In this study evidence of change is evident in cold season discharge from the North Slope region over the 30 year (1981–2010) period examined. There is no significant trend in annual total discharge for the region or its rivers. However, we note that the Kuparuk and nearby Putuligayuk River experienced high annual runoff in 2013, 2014, and 2015 (Stuefer et al., 2017), consistent with expectations under an intensifying arctic hydrological cycle (Wu et al., 2005; Rawlins et al., 2010). Climate models project a future increase in Arctic precipitation that is generally greatest in autumn and winter and smallest in summer, and greatest over the higher latitudes of Eurasia and North America (ACIA, 2005; Kattsov et al., 2007). Higher winter snowfall ~~amounts are possible over~~ across the North Slope ~~, which may, in turn, lead to higher~~ would likely lead to increased freshwater discharges. ~~Though relatively small in magnitude, the simulation produces an increase~~ The model simulation shows increases in cold season discharge of 134% and 215% of the long-term average for the North Slope ~~and Colville basins~~(domain total) and Colville River, respectively. Basins showing a significant increase in cold season discharge cover 45% of the region. Within the Colville basin the ~~change is being driven by processes in headwater subbasins~~ changes are greatest in headwater catchments of the northern foothills and mountains of the Brooks Range (Figure 5b). Landscape conditions in those areas strongly ~~influences~~ influence the quality of water exported during the first half of winter, including the solubility, chemical character, and biodegradability of carbon, nitrogen and other nutrients (Wickland et al., 2018). ~~Mobilization of water through permafrost thaw~~ Effects of permafrost thaw on soil infiltration, flowpath length, and subsurface water movement has been identified ~~as factor~~ in the observed rise in ~~winter (low flow) discharge~~ low flows in parts of the Arctic (St. Jacques and Sauchyn, 2009; Smith et al., 2007; Walvoord and Striegl, 2007). ~~As with the results of the present study,~~ The controls permafrost exerts have been implicated in the observed increase in ~~winter discharge and decrease in~~ the ratio of maximum to minimum monthly discharge in the continuous permafrost regions of the middle and lower ~~part of the~~ Lena River basin ~~reflect the controls permafrost exerts on winter discharge (Gautier et al., 2018)~~(Gautier et al., 2018), linked with increased CSD from 1935–1999 (Yang et al., 2002). More broadly, cold-season low-flow is increasing over most of the pan-arctic (Rennermalm et al., 2010).

Our results also show changes in the proportion of groundwater runoff for the region as a whole, and individually the Colville, Sagavanirktok, and 22 of the other ~~42~~ 40 river basins. Increases are noted across the foothills and higher elevations of the northern Brooks Range. The growing subsurface flows are contributing to the increasing cold season discharge amounts, with the most significant changes in both quantities found across headwaters of several of the larger basins (Colville and Sagavanirktok), as well as areas near the coast east of approximately 140°W. Increases in both subsurface runoff and cold season discharge are ~~very~~ likely manifestations of climate warming, as active layer thaw depths are highly responsive to warming air temperatures (Hinkel and Nelson, 2003). Approximately 20% of the region, the Brooks Range foothills and smaller watersheds near 140°W, shows significant increases in both the fraction of subsurface runoff and active layer thickness. The active layer increase is greatest in those areas experiencing growing subsurface runoff contributions, suggesting a direct connection between thawing soils and changing subsurface flows.

A deepening active layer associated with climate warming will ~~very~~ likely lead to a longer unfrozen period in deeper soils (Yi et al., 2019), enhancing subsurface runoff flow. A deeper active layer delays the soil freeze up and increases the amount of liquid pore water. A larger thawed zone permits additional water storage that supports runoff in late autumn, before soils freeze completely. ~~Diffuse lateral groundwater flow at the land-water boundary in coastal regions can exerts a strong influence on nearshore geochemistry, relative to surface streamflows, in some areas.~~

The changes captured in the modeling are consistent with the notion that permafrost thaw enhances hydrogeologic connectivity and increases low flows in permafrost regions (Bense et al., 2009, 2012; Bring et al., 2016; Lamontagne-Hallé et al., 2018). Observational and modeling studies suggest that permafrost thaw can lead to increased subsurface runoff and cold season discharge, as increasing thickness of the thawed zone and shallow aquifer provide a conduit for flow to rivers

(Walvoord and Striegl, 2007; Bense et al., 2009; Walvoord and Kurylyk, 2016; Lamontagne-Hallé et a Alternatively, these change in continuous permafrost zones can also arise where permafrost is locally discontinuous, or through flow from unfrozen surface water bodies.

Evidence of permafrost thaw and increasing groundwater flow has been reported in ~~recent~~ studies using measurements from arctic rivers. Recent increases in nitrate concentrations and export from the Kuparuk River are consistent with permafrost degradation and deepening flow paths (McClelland et al., 2007). 'Old' carbon measured in Arctic rivers indicates mobilization of pre-industrial organic matter and subsequent transfer to rivers ~~.~~(Schuur et al., 2009; Mann et al., 2015; Dean et al., 2018). St. Jacques and Sauchyn (2009) concluded that increases in winter baseflow and mean annual streamflow in the NWT were caused predominately by climate warming via permafrost thawing that enhances infiltration and deeper flowpaths and hydrological cycle intensification (Frey and McClelland, 2009; Bring et al., 2016). The magnitude of ~~the groundwater~~ subsurface runoff change in the present ~~simulations~~ study should be viewed with caution given the intrinsic resolution of model parameterizations for soil texture, organic layer thickness, and other landscape properties. Our results, however, do point to a close correspondence between active layer thickness and subsurface runoff increases across the foothills of the Brooks Range. ~~This result suggests~~ The enhanced changes there suggest that the relatively thin surface organic layer and sandy soils in the foothills areas may be seeing a relative larger impact on soil warming and thaw. ~~Consistent with our results , a study using~~ Our results thus lend additional support to findings in other recent studies pointing to bigger impacts of warming on permafrost thaw in areas with relatively low vegetation and low soil organic content (Yi et al., 2019; Jones et al., 2019). For example, Yi et al. (2019), using the PWBM in a ~~satellite-based modeling framework~~ modeling framework driven with data from remote sensing observations, found that ALT deepening across much of the Brooks Range has been greater than in the tundra to the north (Yi et al., 2018).

Consistent with recent warming and associated ALT increases, our results suggest an overall decline ($-2$ mm yr$^{2}$) in terrestrial water storage across the North Slope drainage basin over the 1981–2010 period. This decrease is driven by losses in soil ice, with an increase in liquid water storage which does not fully offset the ice losses. With continued warming it is likely that the timing of snowmelt will advance, with impacts to the timing of peak (maximum daily) spring discharge. Averaged across all 42 basins, the date of daily maximum discharge advanced 4.5 days over the 1981–2010 period, though the change is ~~not statistically~~ only marginally significant (p = 0.1) at the 95% confidence level. Individual river basins show larger ~~and more significant~~

shifts to earlier maximum ~~dicharge~~daily discharge. Future changes toward earlier peak discharge can be expected given projections of future warming.

Modeling studies of the impacts of climate warming on permafrost thaw and groundwater discharge are key to our understanding of lateral hydrological flows and associated constituent exports. ~~Given uncertainties in solid precipitation amounts results~~ The underestimate in summer runoff for the Colville River is likely attributable to errors in the meteorological forcings and the model simulation of fluxes including snow sublimation and evapotranspiration. Solid precipitation observations in this region are highly uncertain (Scaff et al., 2015), and this lack of information hinders verification of reanalysis precipitation products and associated studies of changes in seasonal precipitation, which may be playing a role in the hydrological alterations. Results of this study should be corroborated through evaluation of simulations produced with alternate forcings and through parameter sensitivity analysis. The good agreement for the Kuparuk River and the underestimate in simulated discharge for the Umiat subasin of the Colville point to the need for improved estimates of precipitation across higher elevations of the Brooks Range. A fuller understanding of the extent of water cycle alterations in this region will require new ~~measurements of storage and flux terms along with continued development of numerical models~~observations of river discharge, precipitation, snow storage, soil moisture and other key variables needed to parameterize and validate numerical models, including those which capture the important role ground ice plays in runoff generating processes. ~~New discharge observations outside of the freshet period, and in ungaged basins, and associated geochemical sampling can be useful to partition surface and groundwater amounts~~Data being gathered within the region's watersheds and coastal environments can provide important information for model parametrization and verification. Measurements of river discharge and dissolved organic carbon at multiple locations along the coast are critical to an improved understanding of land-ocean carbon exports. Regarding linkages with biogeochemical fluxes, water samples from the mouths of major Arctic river show that dissolved organic carbon in those rivers is sourced primarily from fresh vegetation during the two month of spring freshet and from older, soil-, peat-, and wetland-derived DOC during groundwater dominated low flow conditions (Amon et al., 2012). Stable isotope data obtained from river water samples can be used to guide partitioning of surface and groundwater water flows to better understand how soil drainage and soil moisture redistribution will change with future permafrost thaw and ALT deepening (Walvoord and Kurylyk, 2016).

High performance computing is ~~shedding~~ helping to provide insights into hydrological flows and biogeochemical cycling in arctic environments (Lamontagne-Hallé et al., 2018; Neilson et al., 2018). Improvements in numerical model simulations of groundwater flow regimes in permafrost areas have ~~helped to shed insight~~ provided insights on the important roles that microtopography and soil properties play in groundwater runoff regimes. Model calibration and validation for simulations at finer spatial scales is dependent on new field measurements of parameters such as water table height, active layer thickness, and soil organic carbon content with depth. Simulations for future conditions in the region should take into account processes directly influenced by permafrost thaw (Bense et al., 2012; Lamontagne-Hallé et al., 2018). To overcome challenges in deriving parameterization from multiple disparate data sets, high-resolution ecosystem maps of the Alaska North Slope can provide a convenient upscaling mechanism to parameterize ground soil properties across the region (Nicolsky et al., 2017). Given its considerable effect on soil thermal and hydraulic properties, modeling efforts will benefit from improved mapping of soil organic matter. ~~Measurements and modeling of fluvial biogeochemistry can also help shed insight on changing watershed characteristics influencing water quantity, quality, and associated land-ocean exports.~~

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http://www.geo.umass.edu/climate/data/NSdata.html

## 7 Author Contributions

M.A.R designed the study, executed the model simulations, and performed the analysis. L.C, S.L.S., and D.N. contributed data. M.A.R drafted the initial manuscript and all authors contributed to its development and publication.

**Competing interests:** The authors declare that they have no conflict of interest.

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Table 1: Distribution statistics (cm) for spatial fields of active layer thickness (ALT) from the GIPL and PWBM simulation with MERRA* forcing shown in Figure S3. Also shown are statistics for a simulation using original (non-adjusted) MERRA precipitation (P) data.

| **Active Layer Thick Distribution Statistics (cm)** | | | | | |
|---|---|---|---|---|---|
| **Data** | **5th** | **25th** | **mean** | **75th** | **95th** |
| GIPL | 37.3 | 49.9 | 55.2 | 61.4 | 69.4 |
| PWBM (MERRA) | 30.5 | 40.3 | 50.4 | 58.6 | 75.2 |
| PWBM (MERRA*) | 32.0 | 43.7 | 53.5 | 61.3 | 79.0 |

Table 2: ~~Basin~~ River basin area, annual discharge (Q), and cold season discharge (CSD) for ~~several North Slope~~ the Colville, Kuparuk, and Sagavanirktok rivers and the full North Slope domain. ~~Basins~~ River basins with a significant increase in CSD are indicated with a superscript *. Basin areas are based on their specification in the simulated topological river network.

| **River Basin and Domain-Wide Discharge** | | | |
|---|---|---|---|
| **Basin** | **Area (km$^2$)** | **Annual Q (km$^3$ yr$^{-1}$)** | **CSD (km$^3$ season$^{-1}$)** |
| Colville | 64 095 | ~~10.21~~ 14.0 | 0.023* |
| Kuparuk | 10 054 | ~~1.35~~ 1.4 | 0.004* |
| Sagavanirktok | 16 338 | ~~3.01~~ 3.0 | 0.006 |
| 3 River Total | 90 487 | ~~14.57~~ 18.4 | 0.032 |
| North Slope | 196 061 | ~~28.10~~ 31.9 | 0.116* |

Table 3: Number of grid cells, associated area fraction of domain, and average ALT and $F_{sub}$ for each category shown. ~~Domain~~ Study domain consists of 312 grid cells spanning an area of 196,~~060.8~~ 060 km$^2$ (Figure 1).

| **Number of grids, area, and ALT and $F_{sub}$ averages for each subregion.** | | | | |
|---|---|---|---|---|
| | **N** | **area (%)** | $F_{sub}$ **(%$^3$ yr$^{-1}$)** | **ALT (cm yr$^{-1}$)** |
| $F_{sub}$ increase only | 16 | 5.1 | 0.43 | 0.17 |
| ALT increase only | 211 | 67.6 | 0.05 | 0.75 |
| both | 63 | 20.2 | 0.35 | 1.00 |
| neither | 22 | 7.1 | 0.22 | 0.22 |

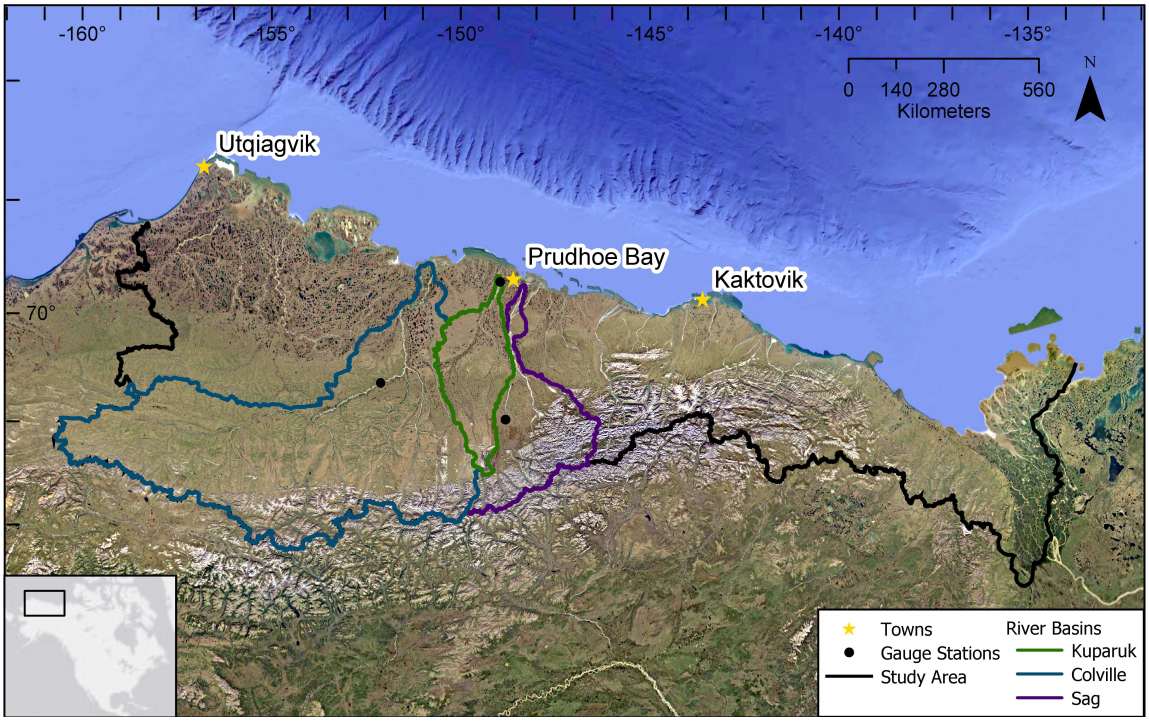

Figure 1: Study domain of North Slope of Alaska. Black line delineates the full North Slope drainage basin. This domain includes all land (196,060 km$^2$) which drains to the Beaufort Sea coast. Blue, green, and purple lines mark boundaries for the drainage basins of the Colville, Kuparuk, and Sagavanirktok rivers, respectively. The three dots mark locations where USGS discharge measurements are obtained for each river at, respectively, Umiat, Deadhorse, and Pump Station #3. The 42 individual basins defined by the simulated topological network (STN) are listed in Table S1. Locations shown for population centers Utqiagvik, Prudhoe Bay, and Kaktovik.

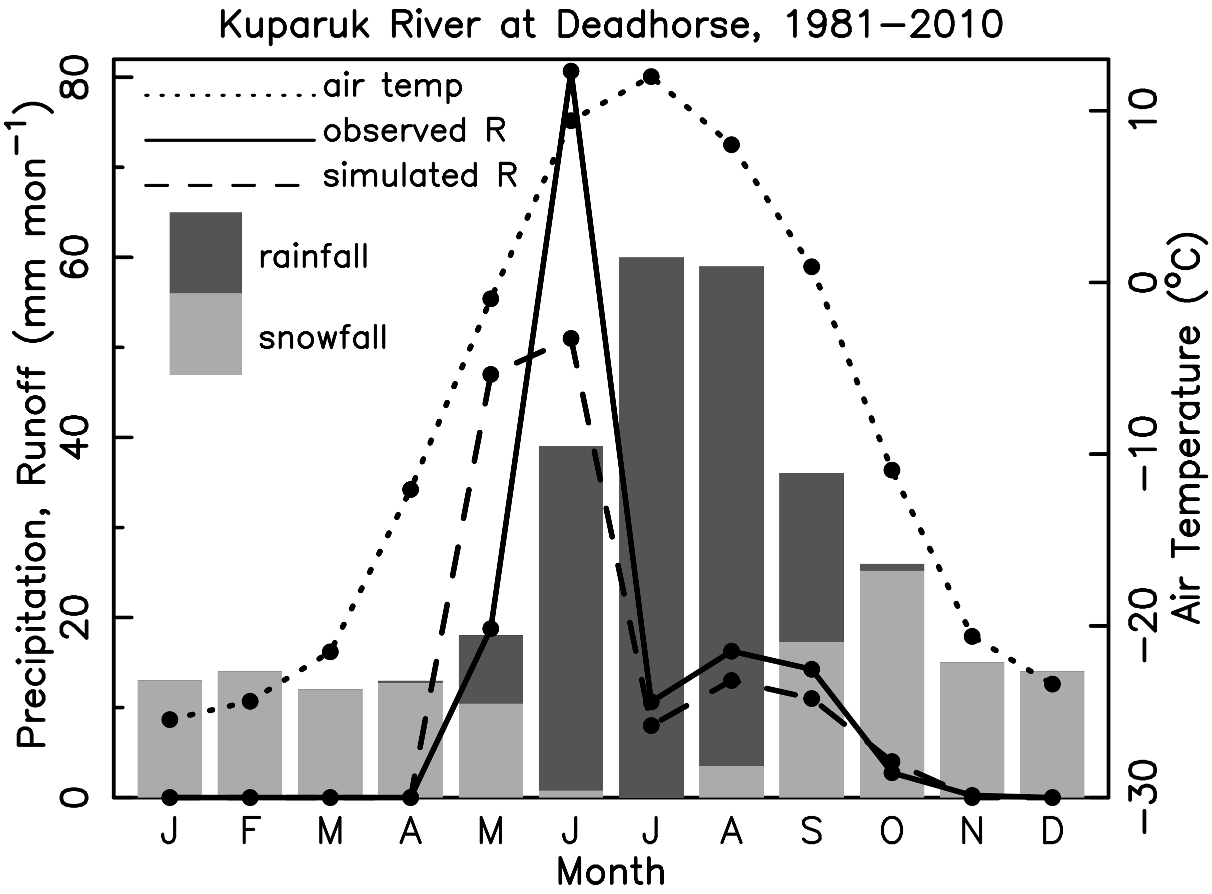

Figure 2: ~~Monthly climatological precipitation (P) and simulated~~ Simulated and observed runoff (R, mm month$^{-1}$) for the Kuparuk River basin 1981–2010. Simulated R expressed in unit depth was calculated from the routed river discharge (Q) volume~~Kuparuk~~. ~~Forcing~~ Observed R was drawn from the USGS database (section 2.1). The PWBM simulation was forced with meteorological data from the MERRA reanalysis, with precipitation adjustment (MERRA*) as described in section 2.2. Monthly air temperature is the average over the Kuparuk basin from the MERRA data used in the model simulation. Monthly climatological precipitation (P) shown in totals (mm month$^{-1}$) for rainfall and snowfall.

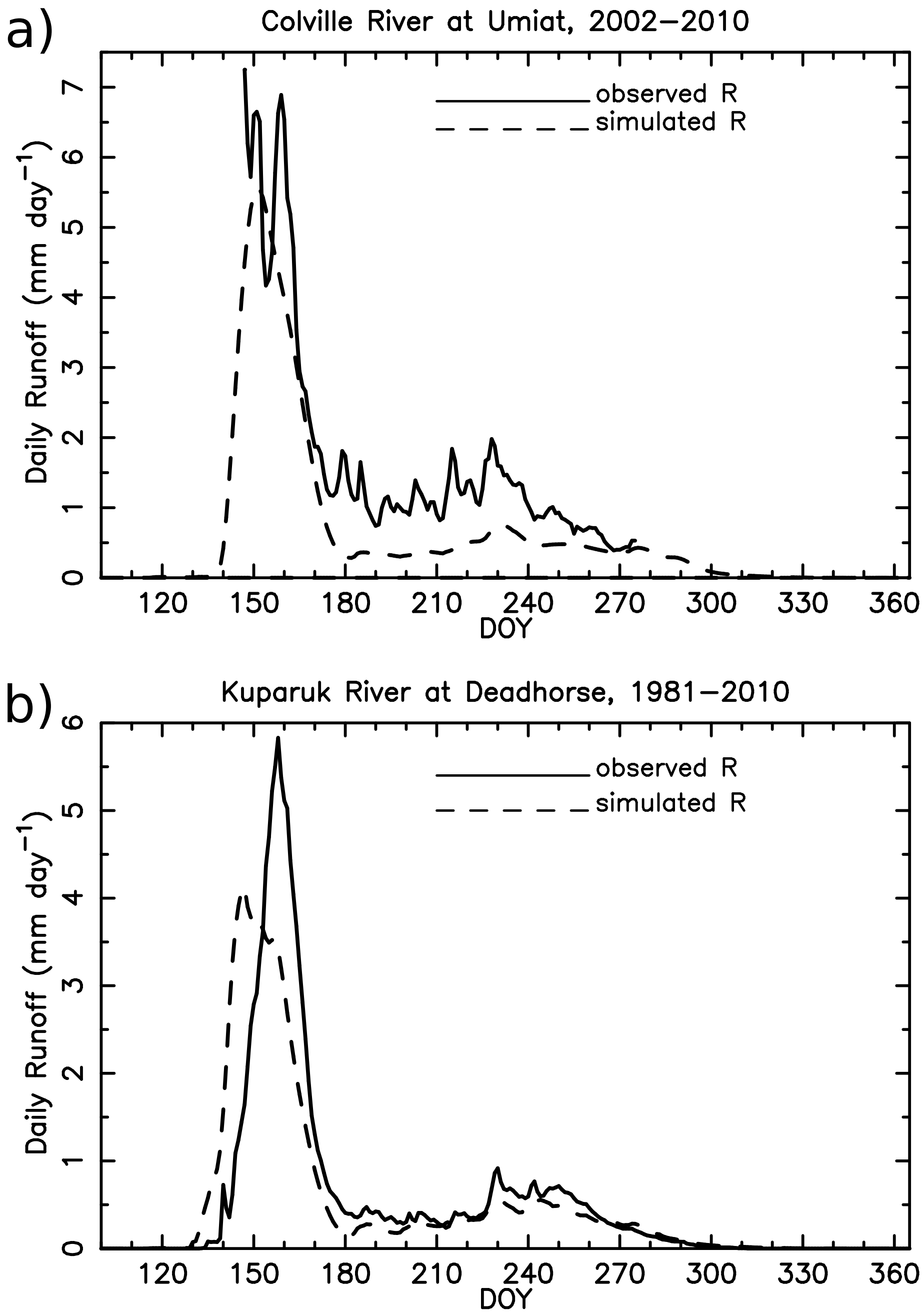

Figure 3: ~~Annual total P from MERRA (adjusted) and simulated~~ Simulated and observed ~~R~~ runoff (R, mm ~~yr~~day$^{-1}$) ~~over~~ for the (a) Colville River at Umiat, AKand (b) Kuparuk ~~basin~~ River at Deadhorse AK. Discharge data for the ~~simulation period 1981–2010~~Colville River published by the USGS are generally available each year from the end of May until early October. Runoff calculated as unit depth as in Figure 2.

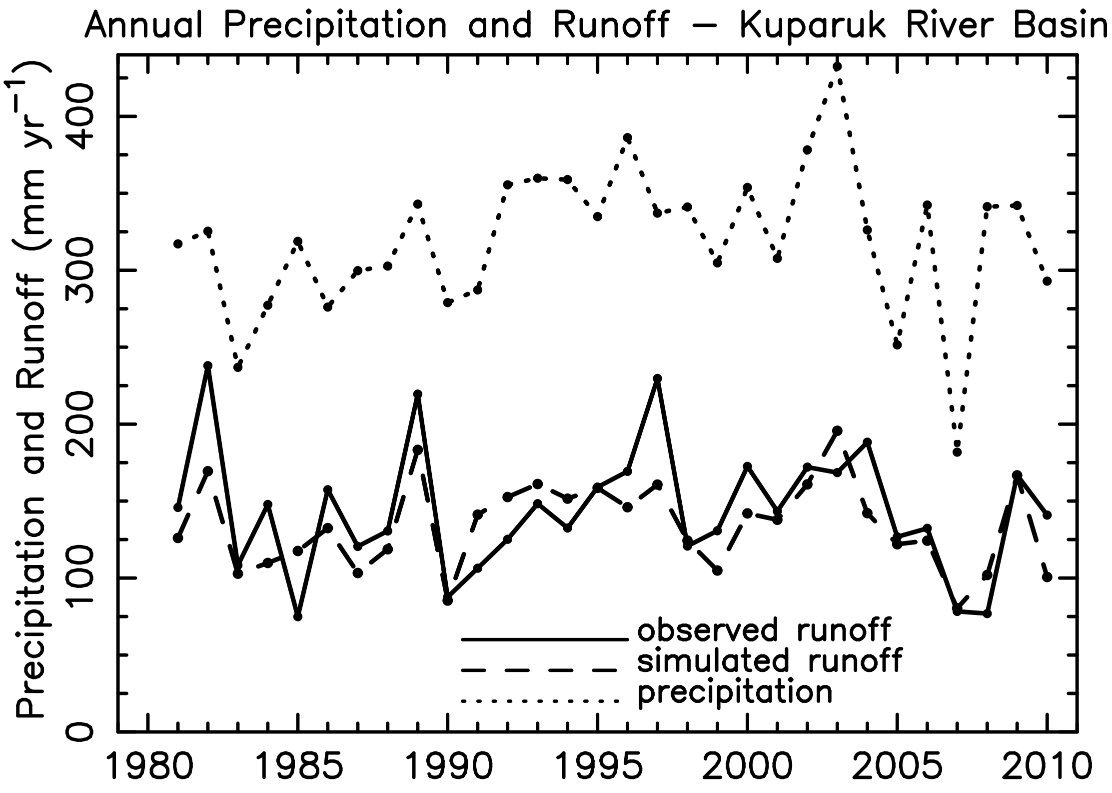

Figure 4: Annual total P from the adjusted MERRA (MERRA*, section 2.2) and simulated and observed R (mm yr$^{-1}$) for the Kuparuk River basin for the simulation period 1981–2010.

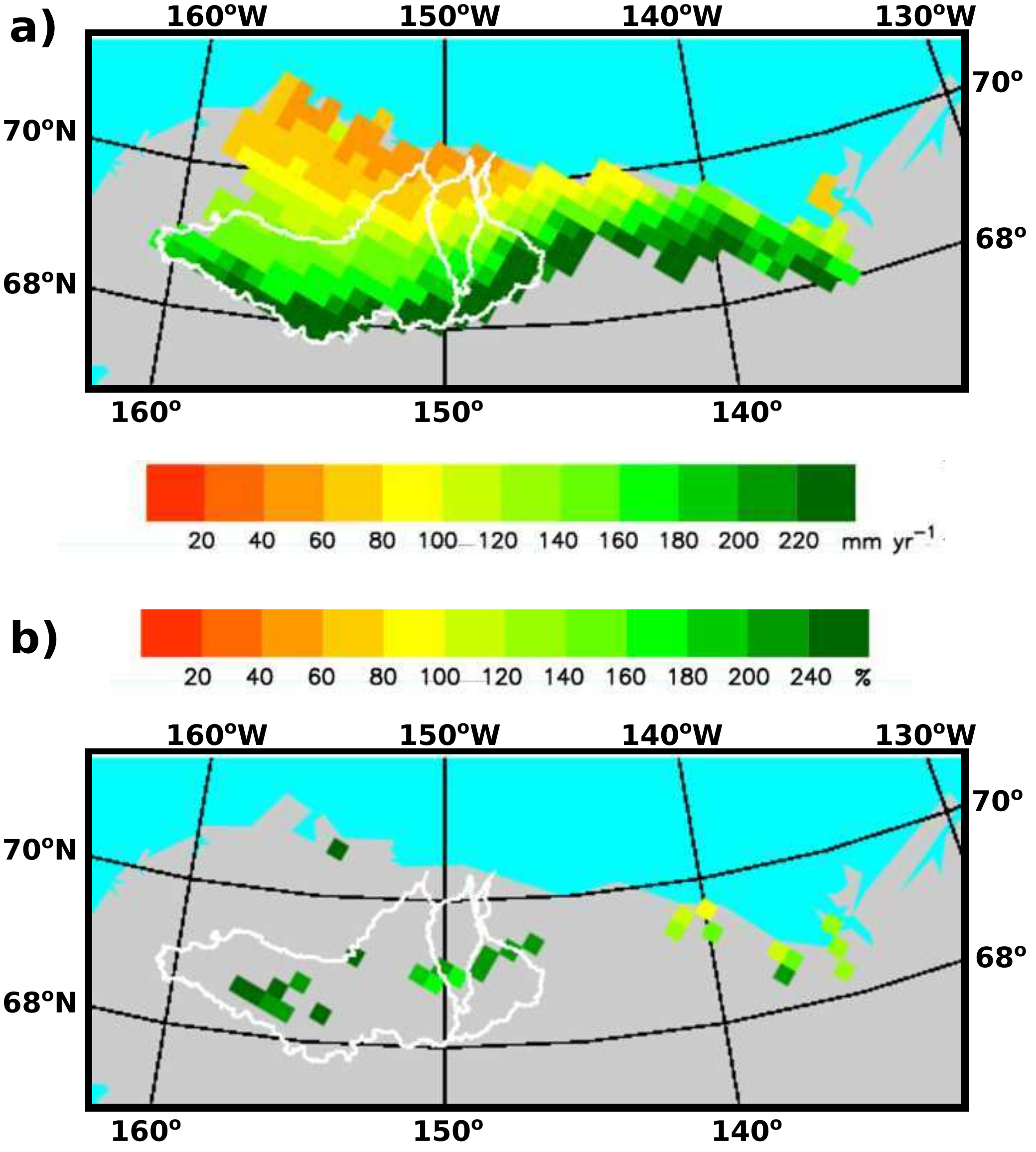

Figure 5: a) Annual total R 1981–2010 (mm yr$^{-1}$) from the model simulation and b) grid cells with a statistically significant ($p < 0.05$) change in simulated cold season (Nov–Apr) Q over the period 1981–2010. The change is shaded as a percentage of the 30 yr average for cold season R for that grid. White outlines are basin boundaries for the (west to east) Colville, Kuparuk, and Sagavanirktok rivers.

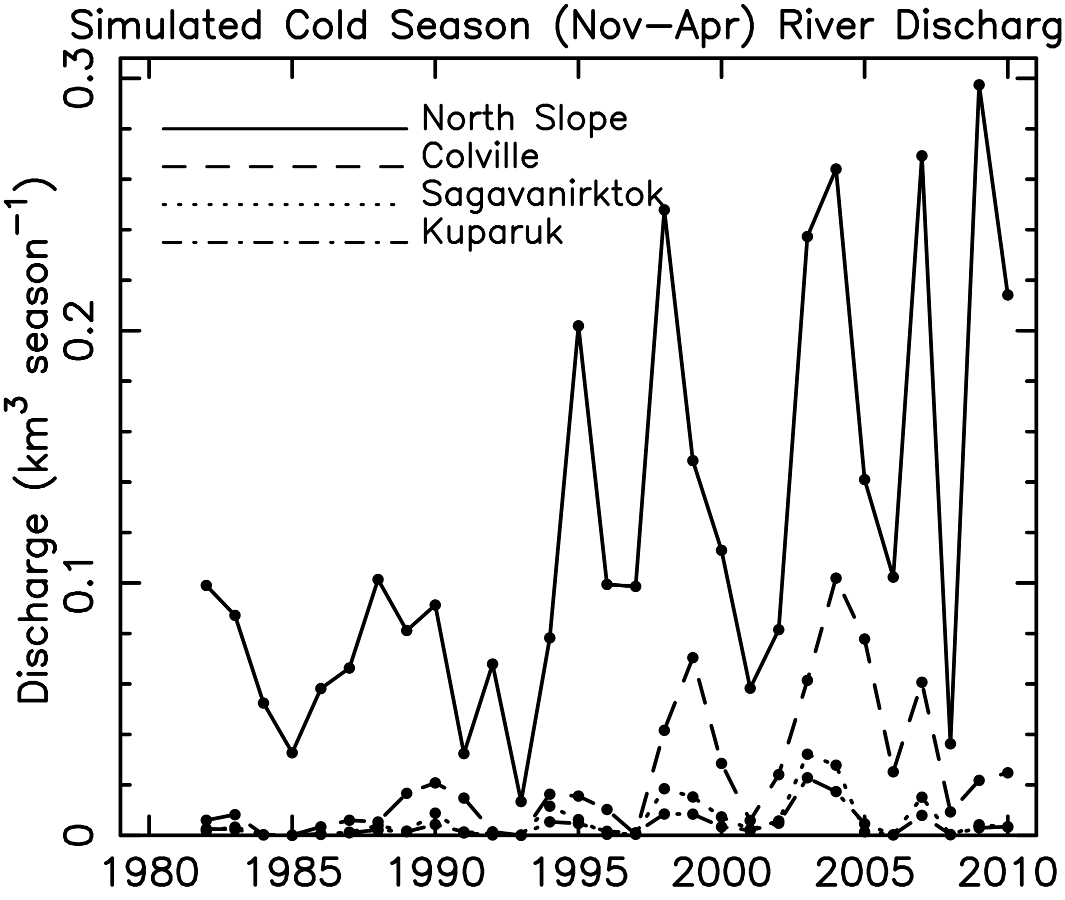

Figure 6: ~~Cold~~ Simulated cold season Q (km$^3$ season$^{-1}$) for the full North Slope region and for separately the Colville, Sagavanirktok, and Kuparuk ~~Rivers~~rivers.

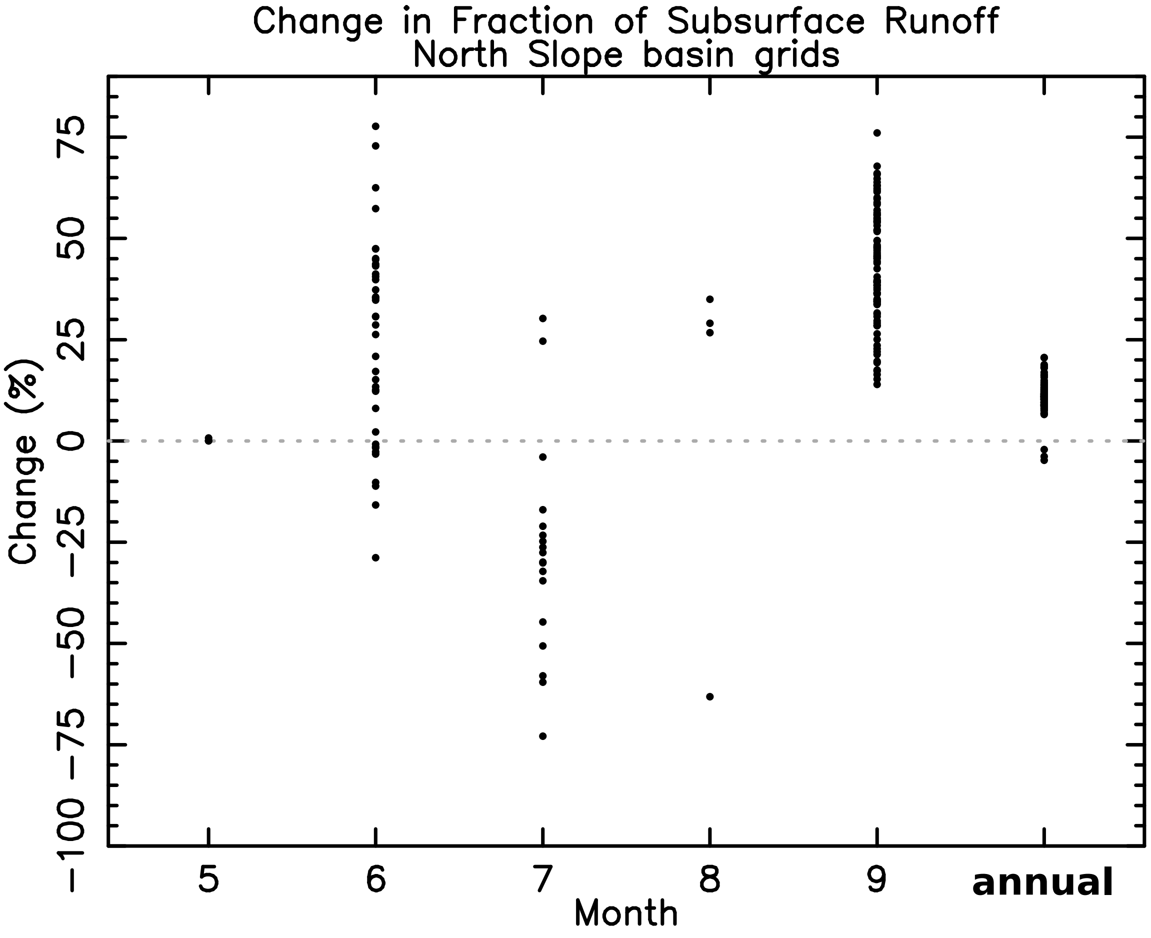

Figure 7: a) ~~Change~~ Grid cell change in fraction of subsurface R ($F_{sub}$) for warm season months May–September and for annual total $F_{sub}$ and R. $F_{sub}$ changes are not defined for other months due to $F_{sub}$ consistently at 100%, or the grid cell having no runoff for that month in more than 50% (15 of 30) of the data years. Change is expressed with respect to the long-term average. Dots represent ~~grids~~ grid cells that show a significant change at $p < 0.05$. Average for grids with a significant change at the annual scale is +11.0%

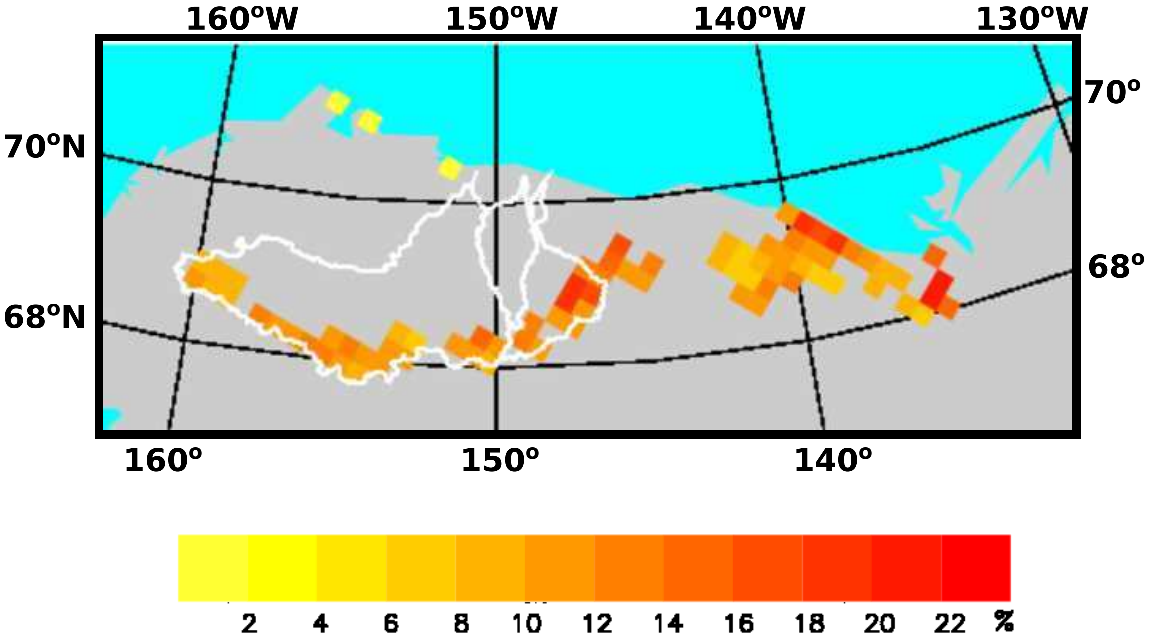

Figure 8: Change in ~~fraction of subsurface R (~~$F_{sub}$ ~~,~~ (%) over the period 1981–2010. Mapped grids show a significant change at $p < 0.05$ based on a two-sided ~~t-~~test.

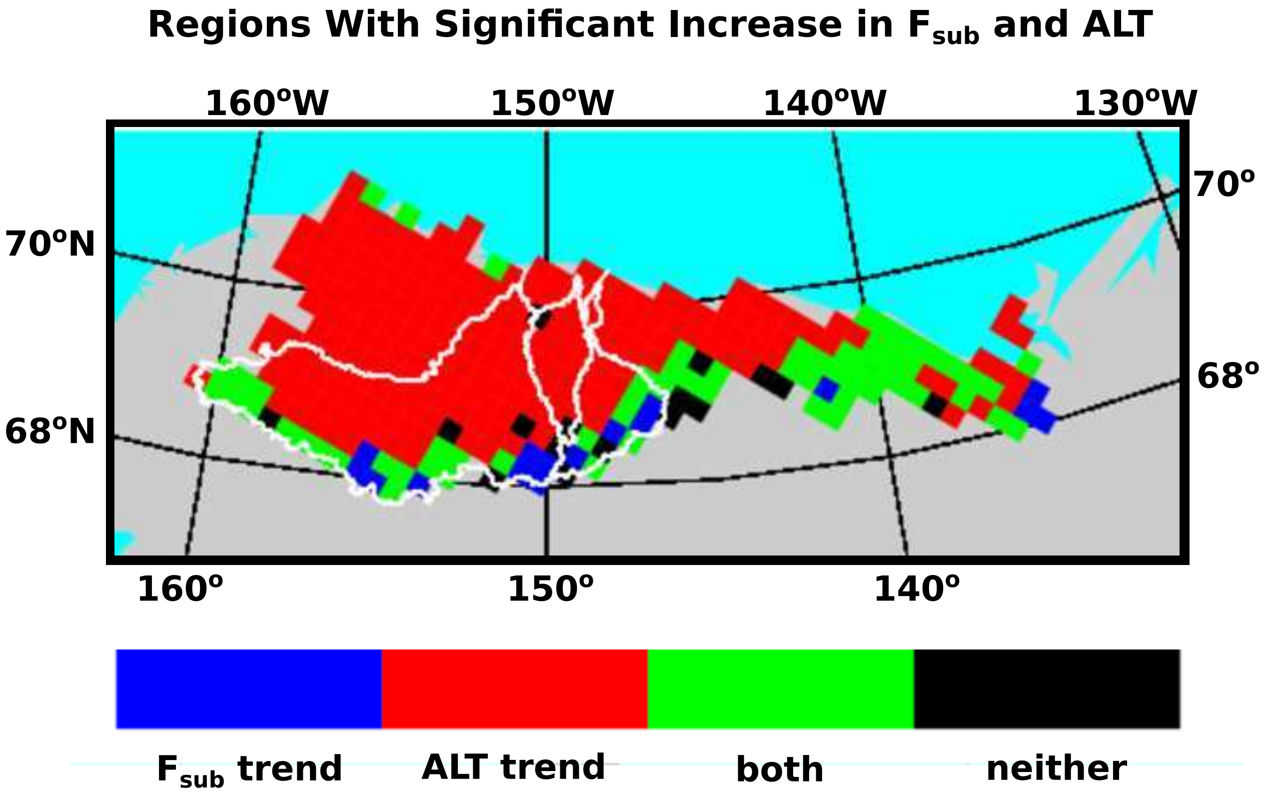

Figure 9: Spatial extent of regions showing a significant increase in annual $F_{sub}$ only (blue), a significant increase in active layer thickness (ALT) only (red), significant increases in both (green), and neither (black). The number of ~~grids~~grid cells, area fraction impacted, and average $F_{sub}$ and ALT increase for each category are shown in Table 3.

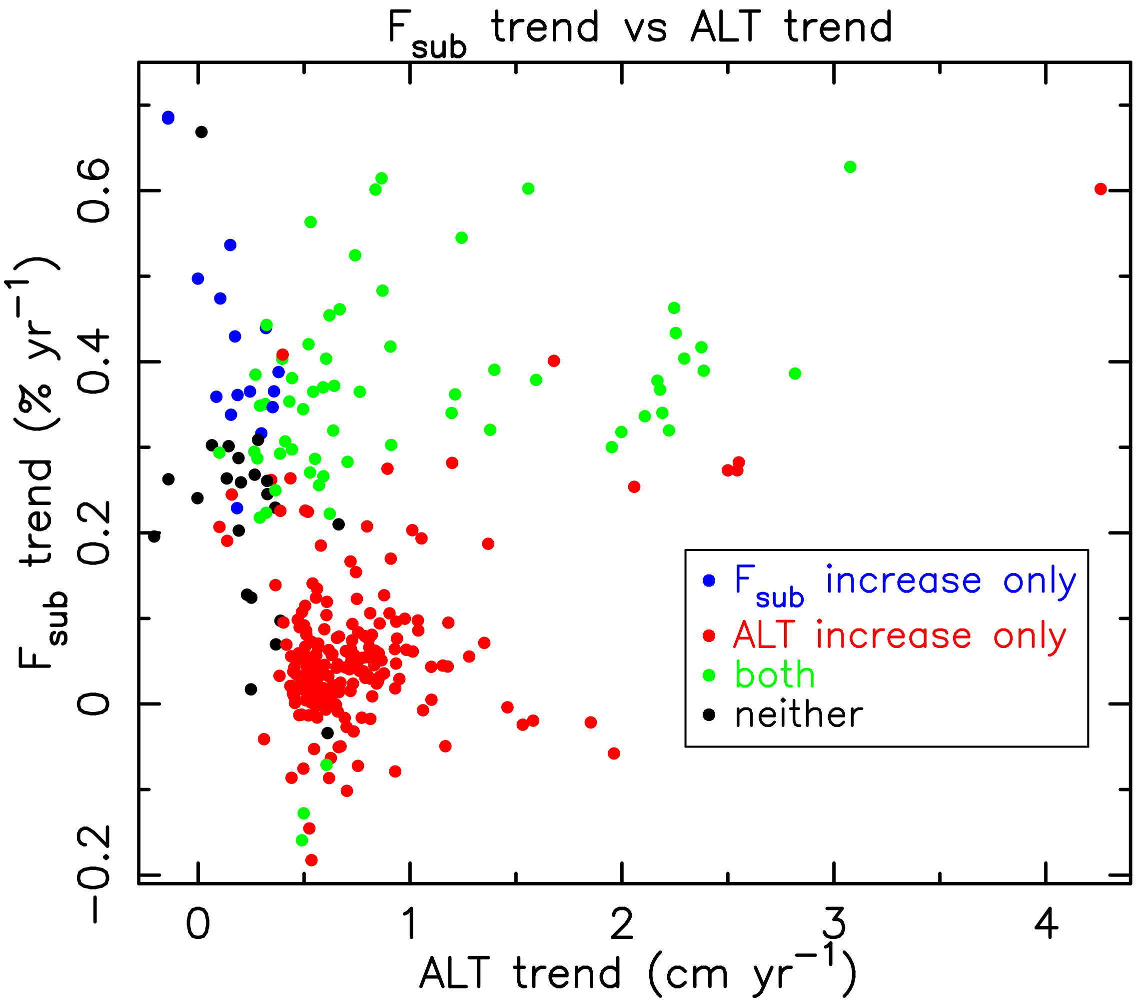

Figure 10: Increase in annual $F_{sub}$ (% yr$^{-1}$) vs increase in seasonal maximum ALT (cm yr$^{-1}$) for all 312 domain grid cells. ~~The number of grids, areal percent, and average $F_{sub}$ and ALT increase for each category shown~~ Relevant statistics are listed in Table 3.

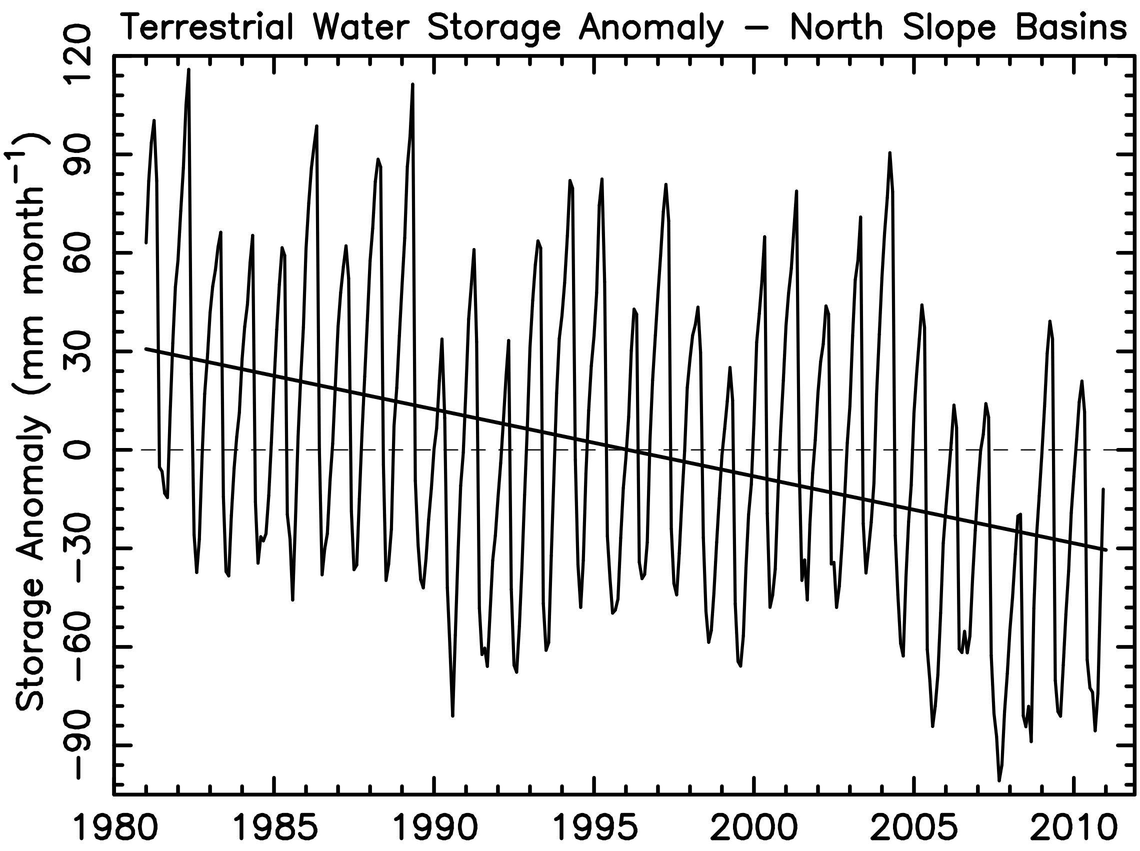

Figure 11: Terrestrial water storage (TWS) anomaly (mm month$^{-1}$) as an average across the North Slope drainage basin. Anomaly is with respect to the long-term average (1981–2010). In the ~~model~~ PWBM, TWS includes soil liquid water, ice, and snow storage. It does not include water stored in permanent water bodies such as ponds and lakes.

Table S1: River basins ordered by size for the North Slope drainage region. Basins in the simulated topological network (STN) were defined on the 25×25 km$^2$ EASE-Grid (Brodzik and Knowles, 2002). Areas in km$^2$ based on extent in the STN of the full drainage basin ~~info~~expressed to the respective river mouth at the coast. Names listed for rivers with areas greater than 4000 km$^2$. Unnamed rivers are numbered by size among all river basins in the pan-Arctic STN.

| **Latitude** | **~~lon~~Longitude** | **Basin area** | **Name** |
|---|---|---|---|
| 70.3288 | -151.0736 | 64095 | Colville |
| 70.6501 | -154.3348 | 18851 | ~~GHAASBasin534~~ Ikpikpuk |
| 70.2604 | -148.1340 | 16338 | ~~GHAASBasin589~~ Sagavanirktok |
| 70.9372 | -156.1757 | 12568 | Meade |
| 70.3802 | -148.6959 | 10054 | Kuparuk |
| 69.4239 | -139.4672 | 6284 | ~~GHAASBasin1139~~ Firth |
| 70.0799 | -146.1292 | 5655 | Canning |
| 69.8753 | -144.1624 | 5027 | ~~GHAASBasin1302~~ Hulahula |
| 70.0150 | -147.0306 | 4399 | ~~GHAASBasin1403~~ Shaviovik |
| 68.5119 | -135.8551 | 4399 | ~~GHAASBasin1453~~ Unnamed |
| 70.8438 | -155.5560 | 3770 | ~~GHAASBasin1659~~ Basin 1659 |
| 69.5061 | -141.7360 | 3142 | ~~GHAASBasin1882~~ Basin 1882 |
| 68.6613 | -137.1530 | 3142 | ~~GHAASBasin1896~~ Basin 1896 |
| 69.9243 | -143.2594 | 2514 | ~~GHAASBasin1949~~ Basin 1949 |
| 69.7866 | -142.7447 | 2514 | ~~GHAASBasin1966~~ Basin 1966 |
| 69.1231 | -138.5215 | 2514 | ~~GHAASBasin2012~~ Basin 2012 |
| 68.6711 | -136.2922 | 2514 | ~~GHAASBasin2041~~ Basin 2041 |
| 69.6471 | -142.2369 | 2514 | ~~GHAASBasin2104~~ Basin 2104 |
| 68.8289 | -136.7357 | 1885 | ~~GHAASBasin2279~~ Basin 2279 |
| 68.9706 | -138.0587 | 1885 | ~~GHAASBasin2354~~ Basin 2354 |
| 70.1386 | -147.5789 | 1885 | ~~GHAASBasin2463~~ Basin 2463 |
| 69.5720 | -139.9503 | 1885 | ~~GHAASBasin2464~~ Basin 2464 |
| 68.6760 | -135.4308 | 1885 | ~~GHAASBasin2466~~ Basin 2466 |
| 71.2383 | -156.5290 | 1257 | ~~GHAASBasin3496~~ Basin 3496 |
| 70.9549 | -154.6538 | 1257 | ~~GHAASBasin3497~~ Basin 3497 |
| 70.3011 | -149.6013 | 1257 | ~~GHAASBasin3498~~ Basin 3498 |
| 69.9515 | -145.5915 | 1257 | ~~GHAASBasin3500~~ Basin 3500 |
| 69.8212 | -145.0607 | 1257 | ~~GHAASBasin3501~~ Basin 3501 |
| 69.2742 | -138.9909 | 1257 | ~~GHAASBasin3503~~ Basin 3503 |
| 69.3244 | -135.4441 | 1257 | ~~GHAASBasin3504~~ Basin 3504 |
| 70.8546 | -152.5256 | 628 | ~~GHAASBasin4393~~ Basin 4393 |
| 70.4159 | -150.1729 | 628 | ~~GHAASBasin4394~~ Basin 4394 |
| 69.5415 | -140.8446 | 628 | ~~GHAASBasin4398~~ Basin 4398 |
| 69.0003 | -135.4374 | 628 | ~~GHAASBasin4409~~ Basin 4409 |
| 68.8388 | -135.0000 | 628 | ~~GHAASBasin4410~~ Basin 4410 |
| 69.3244 | -134.5559 | 628 | ~~GHAASBasin4416~~ Basin 4416 |
| 69.4845 | -134.1048 | 628 | ~~GHAASBasin4419~~ Basin 4419 |
| 71.1461 | -155.8978 | 628 | ~~GHAASBasin6501~~ Basin 6501 |
| 70.4384 | -151.6543 | 628 | ~~GHAASBasin6502~~ Basin 6502 |
| 70.0604 | -143.7812 | 628 | ~~GHAASBasin6507~~ Basin 6507 |
| 68.8167 | -137.6026 | 628 | ~~GHAASBasin6511~~ Basin 6511 |
| 69.1605 | -135.8814 | 628 | ~~GHAASBasin6513~~ Basin 6513 |

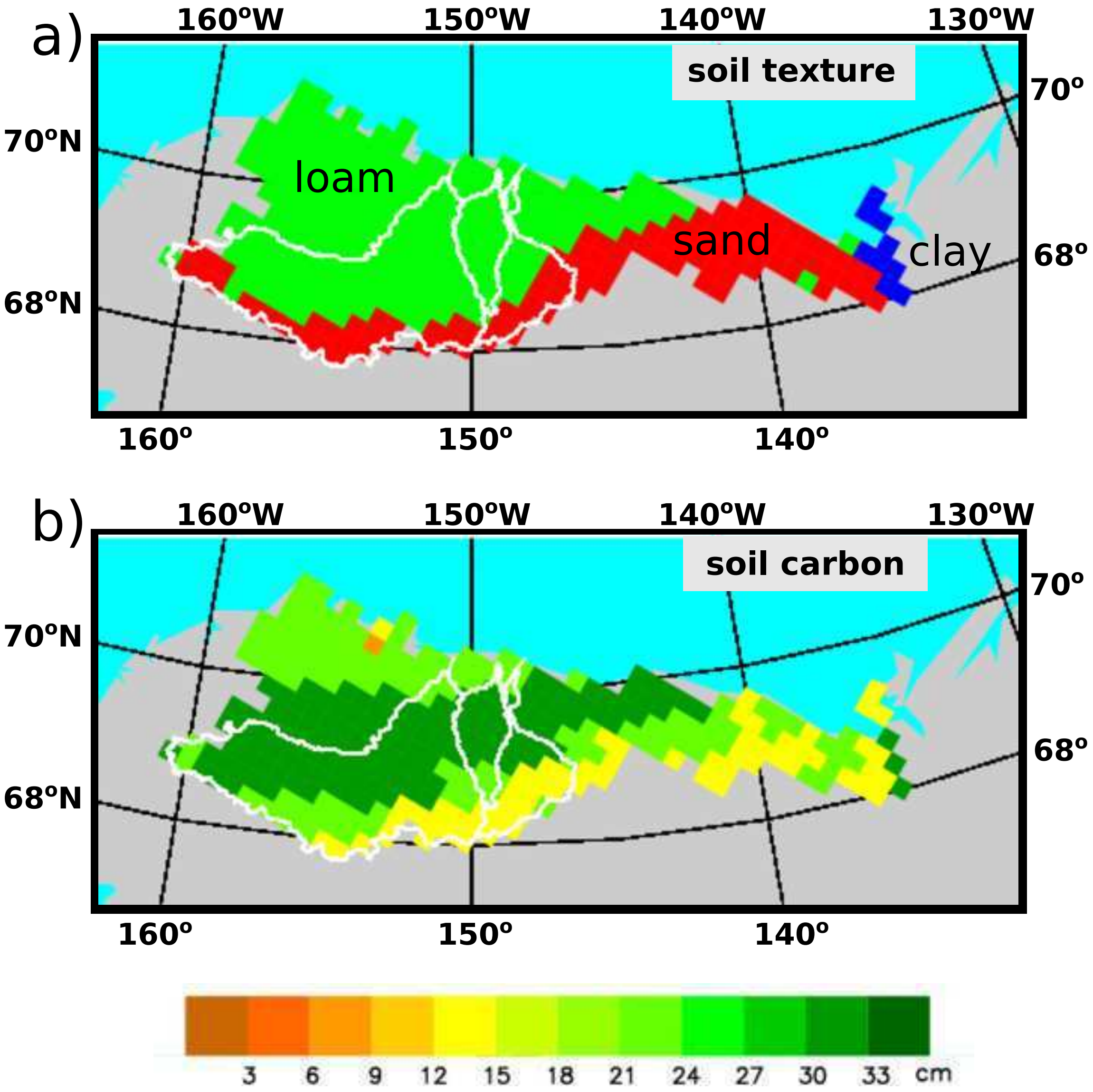

Figure S1: a) Soil texture classes and b) thickness of surface soil carbon layer used in model parameterizations. Soil textures are drawn from the UNESCO Food and Agriculture Organization's Digital Soil Map of the World (Food and Agriculture Organization/UNESCO, 1995). Soil carbon is taken from the Northern Circumpolar Soil Carbon Database (NCSCD) (Hugelius et al., 2014). Soil carbon thickness derived from the NCSCD data and used in the PWBM includes all soil layers for which some amount of carbon is present. Primarily mineral soil exists downward over the remainder of the soil column.

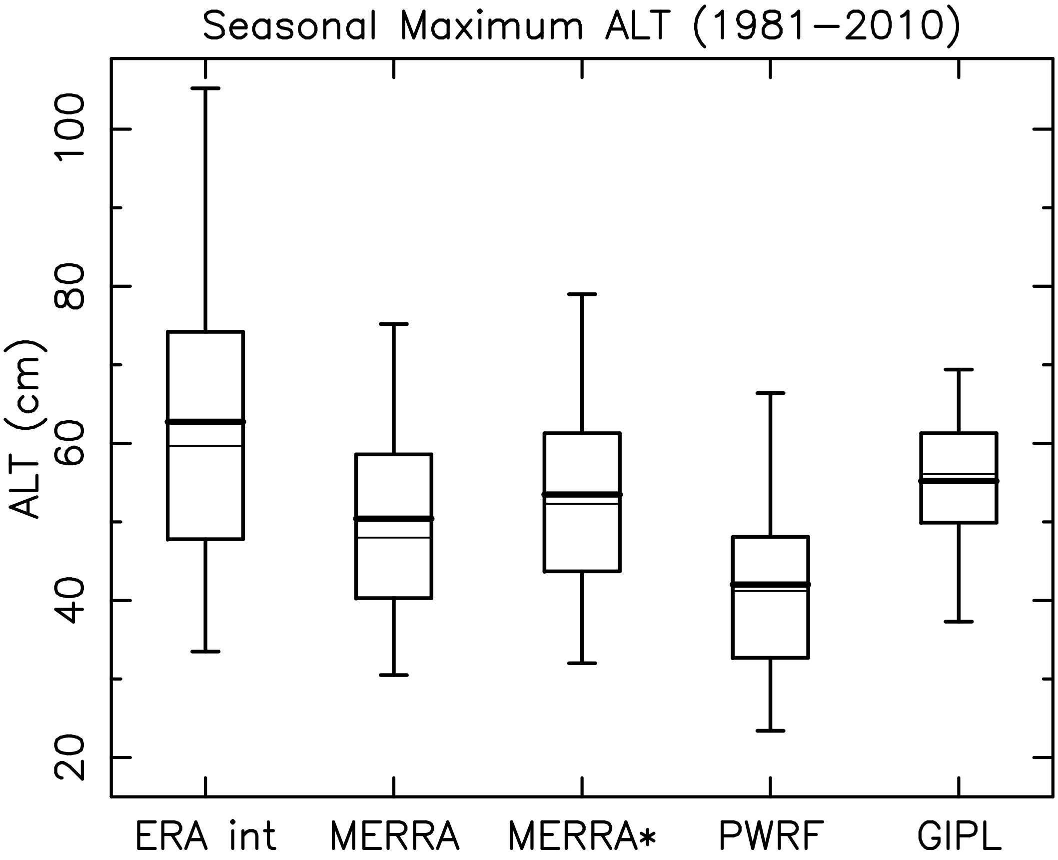

Figure S2: a) Seasonal maximum ALT (cm) as an average over the period 1981–2010 from PWBM simulations and the GIPL model. Boxplots represent the 217 (of 312) PWBM domain grid cells for which GIPL ALT data are available. Boxplots were drawn from PWBM simulation using climate forcings from ERA interirum, MERRA, MERRA with precipitation adjustment (MERRA*), and Polar WRF. Heavy line in each box is the distribution mean. Thin line is the distribution median. Boxes bracket the 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. From PWBM soil temperatures the seasonal maximum ALT is calculated as the depth to which the 0 °C penetrates each summer. Nicolsky et al. (2017) provide details on the GIPL ALT.

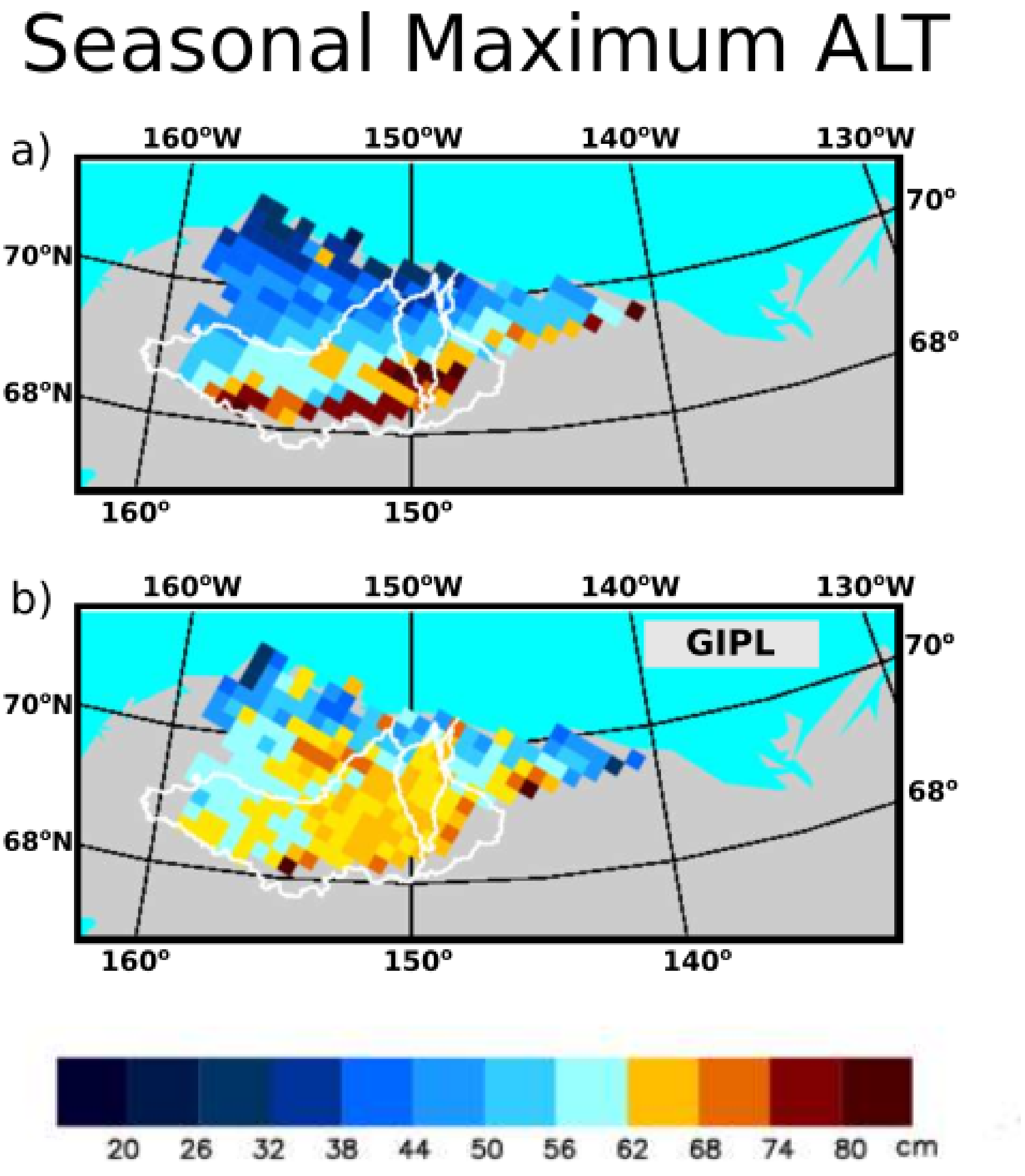

Figure S3: a) Seasonal maximum ALT (cm) as an average over the period 1981–2010 from a) PWBM with MERRA* forcing and b) GIPL.~~Evaluations are made for the 217 (of 312) domain grid cells which have GIPL ALT data. For PWBM the seasonal maximum ALT is calculated as the depth to which the 0 °C penetrates each summer. Nicolsky et al. (2017) provides details on the GIPL ALT.~~

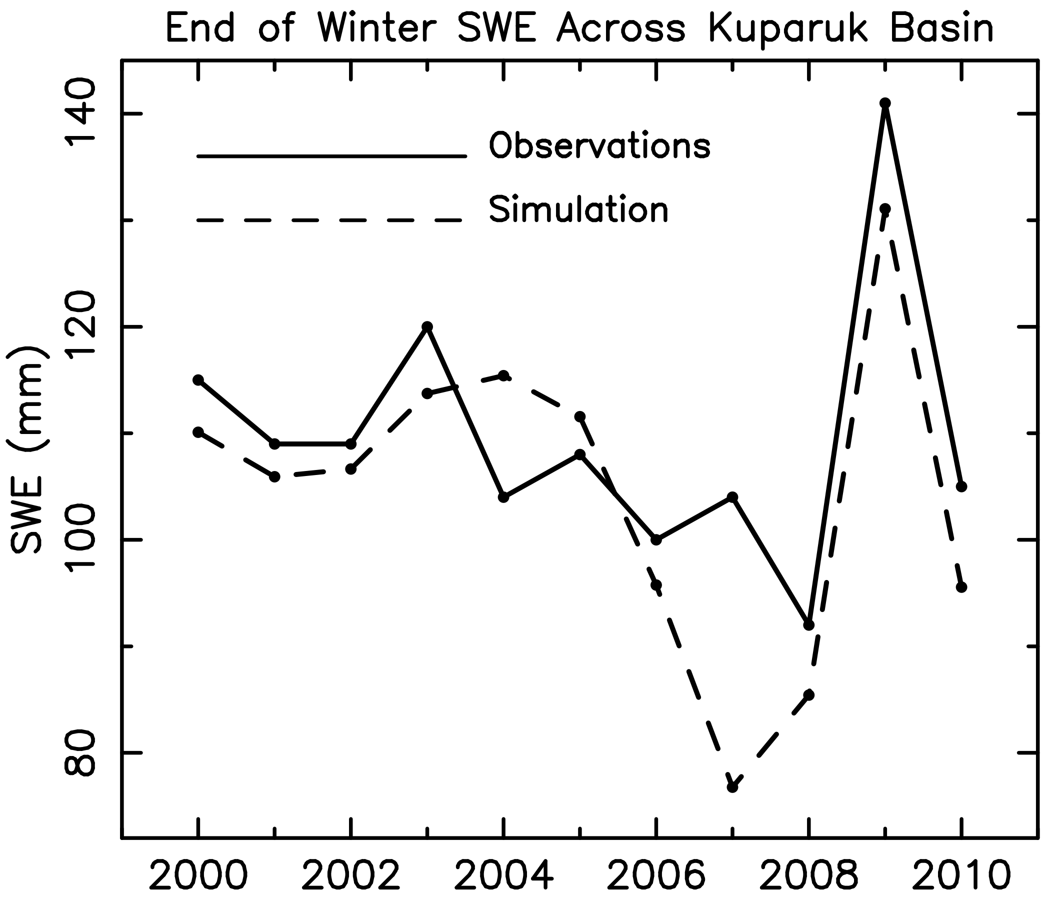

Figure S4: Observed and model simulated end of winter snow water equivalent (SWE, mm) for the Kuparuk River basin 2000–2010. Observed values represent an average of measurements made across the basin as described by Stuefer et al. (2013). Simulated end of season SWE is calculated as the average between 24 April and 7 May each year.

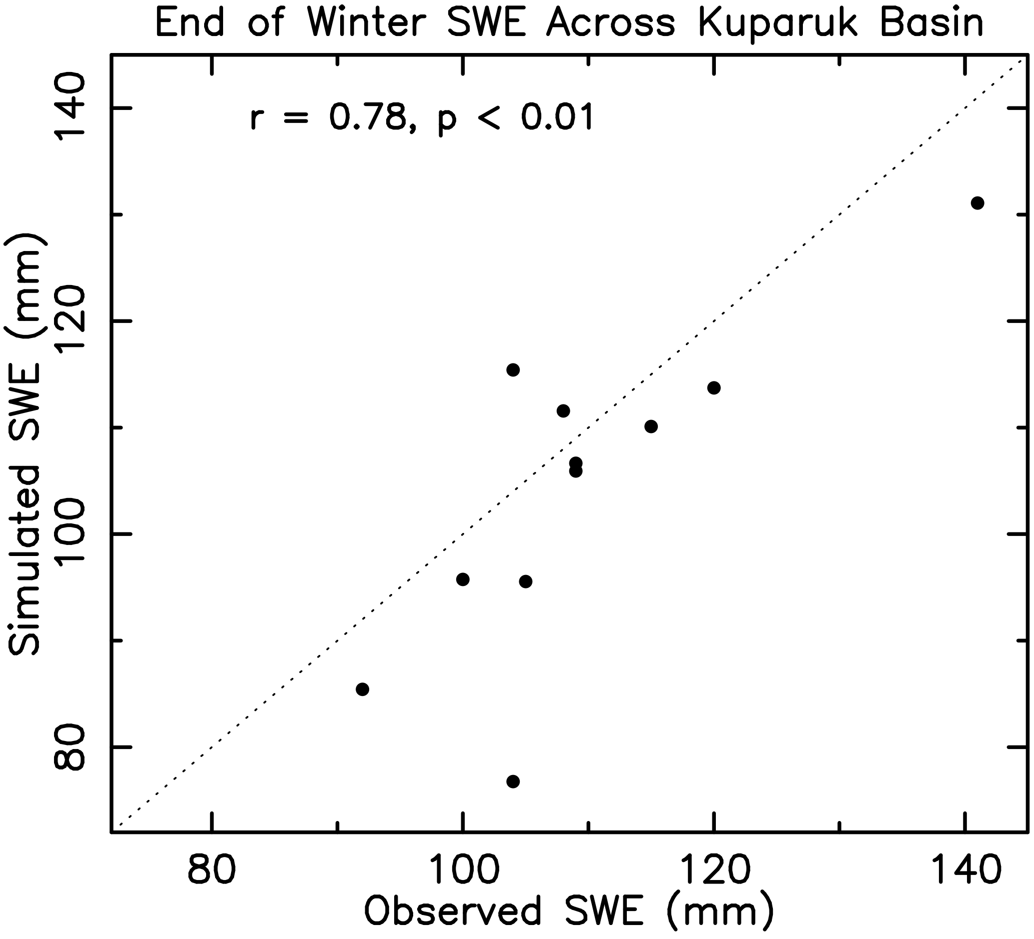

Figure S5: Observed and model simulated end of winter SWE (mm) for the Kuparuk Basin 2000–2010.

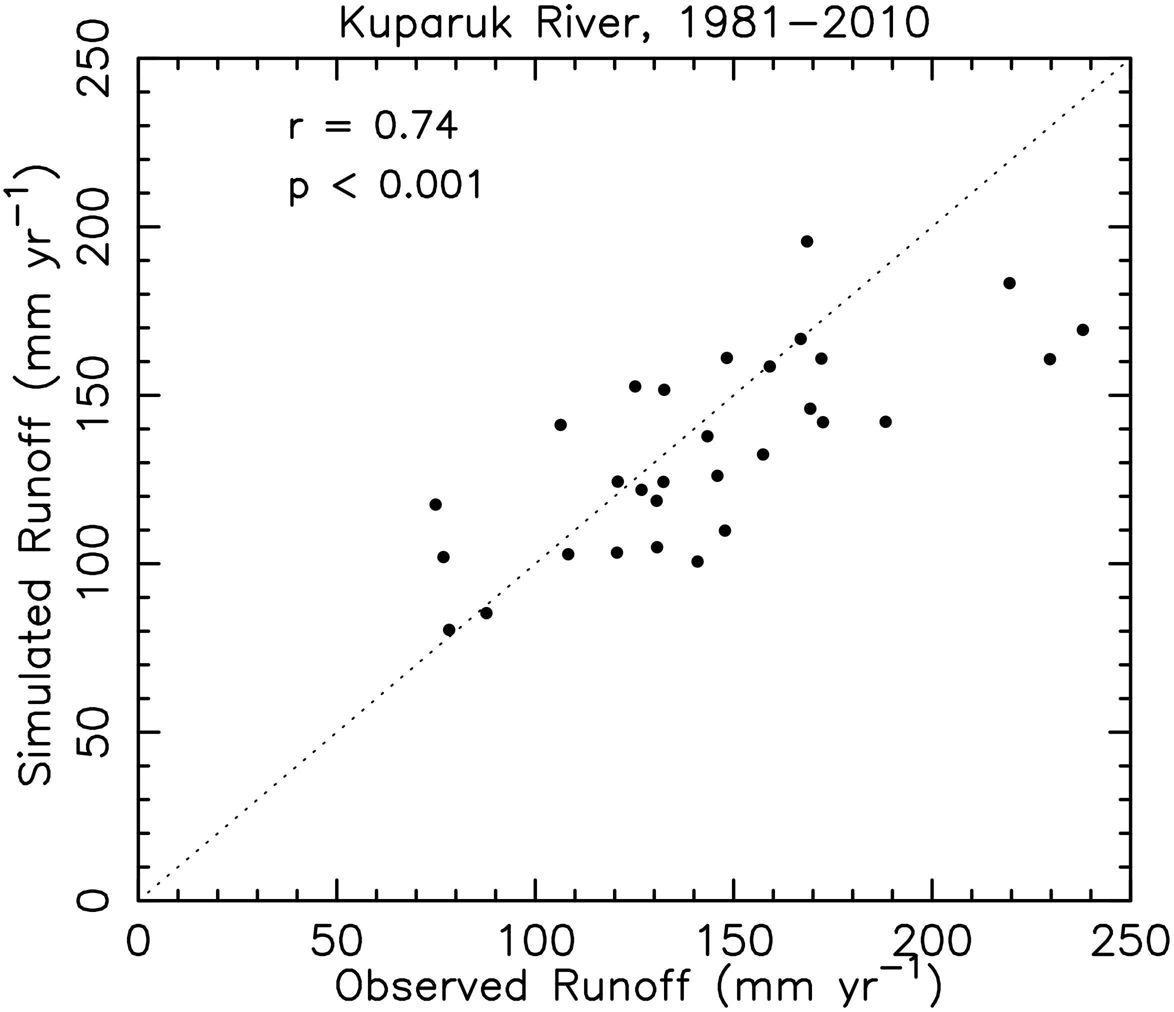

Figure S6: Simulated vs. observed annual total R (mm yr$^{-1}$) for the Kuparuk basin. Correlation coefficient (LLS) is $r = 0.73$ ($p < 0.001$).

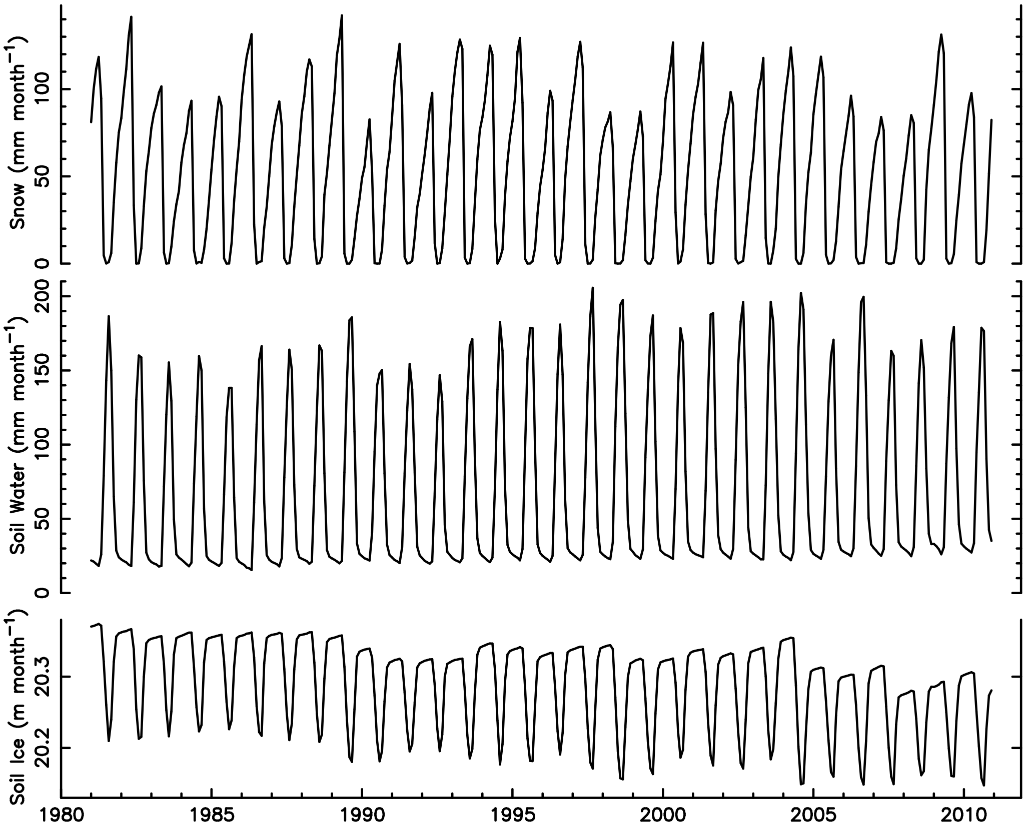

Figure S7: Monthly water storage for snow (solid and liquid portions, mm month$^{-1}$), soil water (mm month$^{-1}$), and soil ice (m month$^{-1}$) as an average across the North Slope drainage basin. Amounts are totaled over the full 60 m model soil column

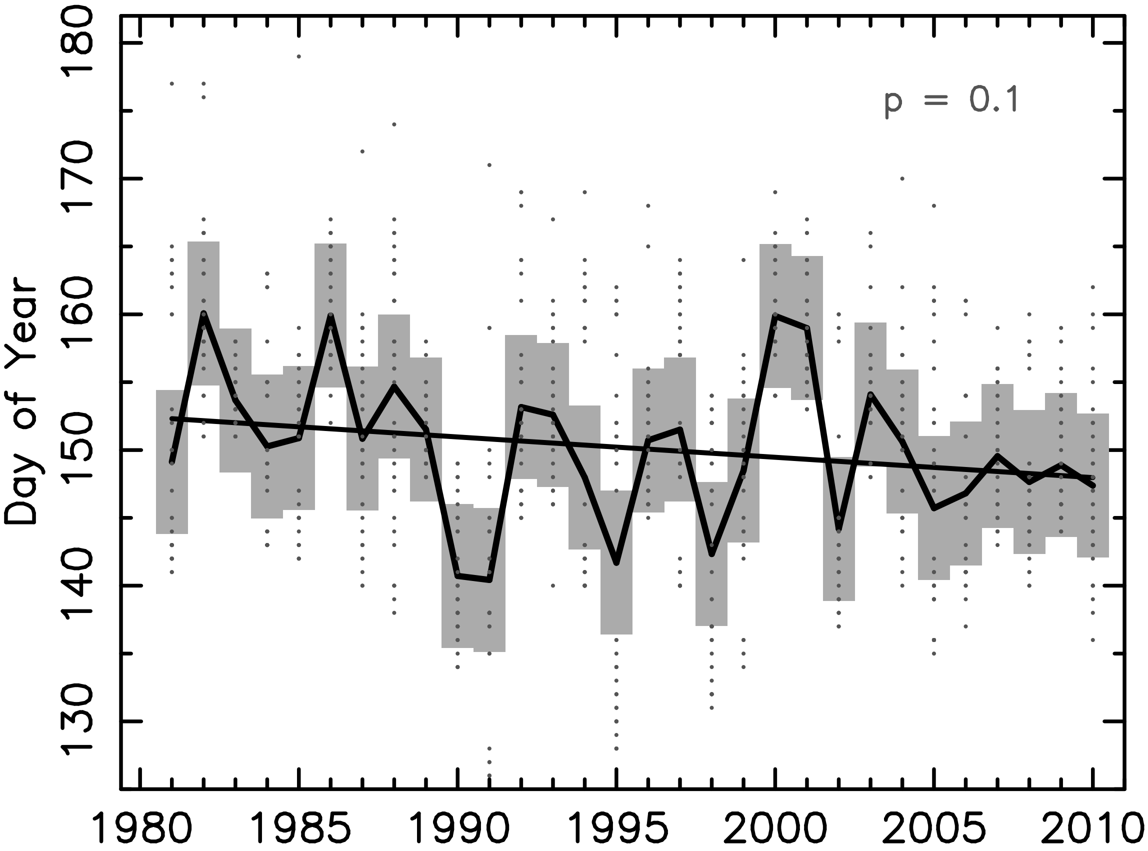

Figure S8: Date of maximum ~~river~~ daily Q 1981–2010 for all 42 North Slope rivers. Gray bar shows the 1-$\sigma$ range around the average date (solid line). Dots indicate the date for each ~~basin~~river. Linear least squares trend shown. Significance of linear trend (GLM) is approximately $p = 0.1$