Changing Arctic River Dynamics Cause Permafrost Thaw

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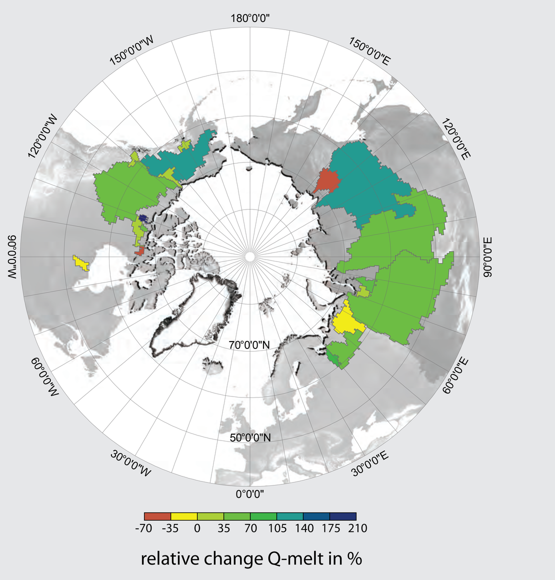
How do hydrological changes in Arctic river systems, affect permafrost conditions?

Degradation of ice-rich permafrost is caused by rapid Arctic warming. Likely this degradation already has altered the water balance by increasing runoff and flooding. Instrumental streamflow records indicate a 9.8% increased discharge (1977-2007) for 19 large Arctic rivers in Canada and Eurasia [Overeem and Syvitski, 2010]. There is also a shift of maximum discharge to earlier in the summer, most likely due to earlier snowmelt.

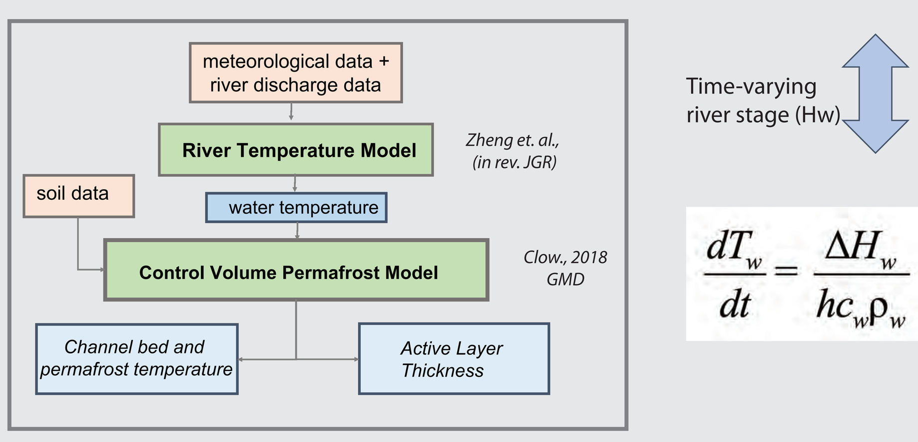


Arctic river discharges have been increasing over the last few decades (1977-2007)

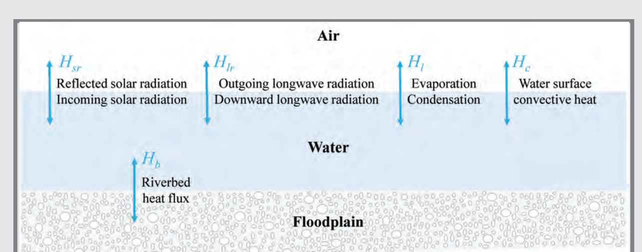
How does river flooding affects permafrost thermal state in floodplains and deltas?

How is permafrost affected by the timing of river flooding changes with Arctic warming?

Modeling of thermal regimes of rivers and permafrost



Flowchart of coupled models of newly developed river temperature and CVPM; required climatological and soil properties input data and predicted outputs



$$\frac{dT_w}{dt} = \frac{\Delta H_w}{h c_w \rho_w}$$

$$\Delta H_w = H_{sr} + H_{lr} + H_l + H_c + H_b$$

H_w = Net heat change; H_{sr} = Net solar radiation; H_{lr} = Net longwave radiation; H_l = Latent heat flux; H_c = Surface convective heat; H_b = Riverbed heat flux

Energy Balance Model for the River Temperature Model

We developed a first-order heat budget approach to simulate evolving river flood water temperature over the seasonal inundation period. Solar radiation, air temperature and wind control the different components of heat exchange between the atmosphere and the river water surface. An additional term specifically calculates the exchange of heat between the river water and the channel bed and subsurface. Then, this river and flood water temperature is coupled to the Control Volume Permafrost Model (CVPM), which models detailed thermal state of shallow permafrost.

Permafrost Model Toolbox Codes are available on Github : https://github.com/csdms-contrib/CVPM/tree/v1.1. and Overeem et al., 2018; https://github.com/permamodel

Model Validation for the Kuparuk River in Alaska

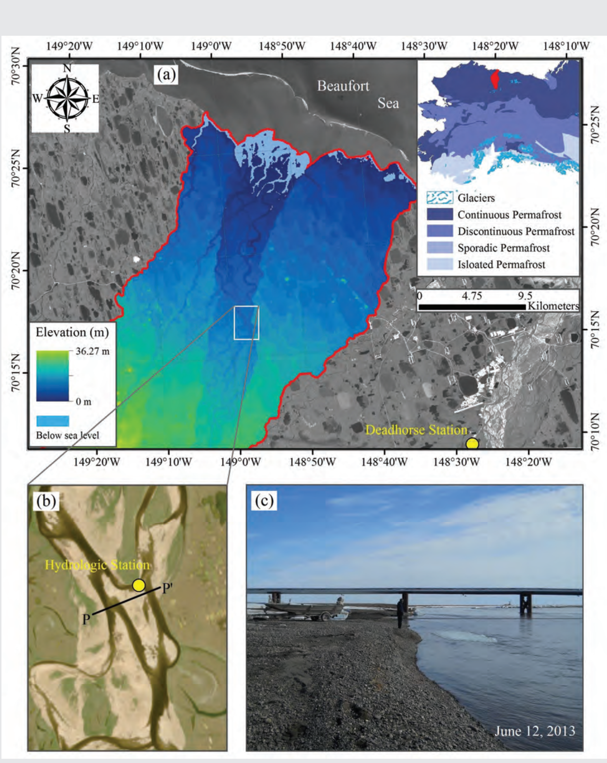


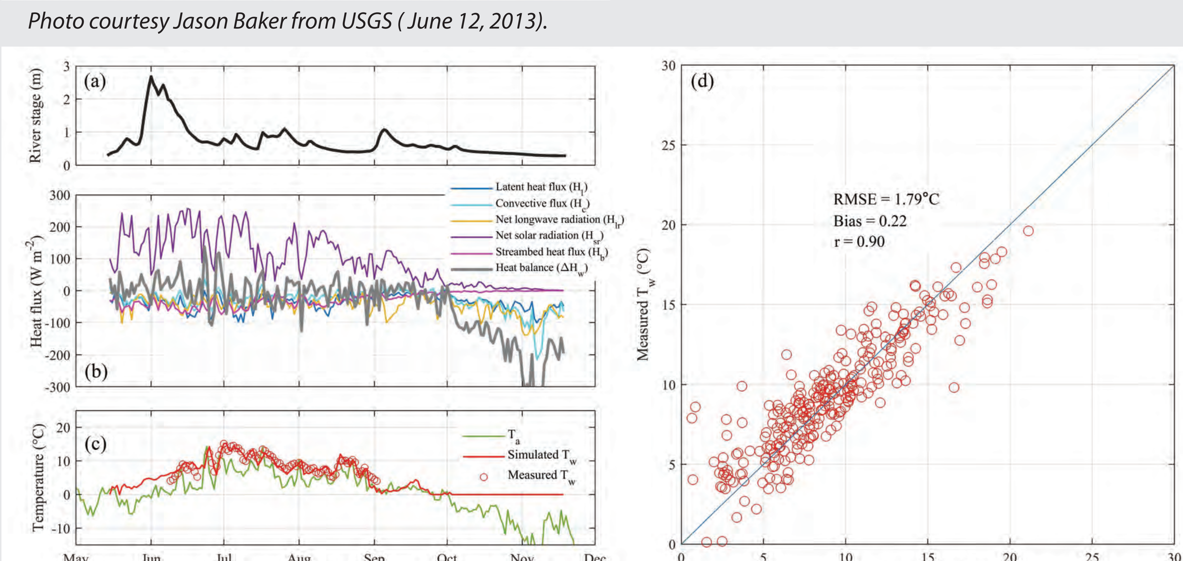
Photo courtesy Jason Baker from USGS (June 12, 2013).

We apply the combined model to the Kuparuk river floodplain and delta, a medium-sized river system on the North Slope of Alaska. The river basin is in the zone of continuous permafrost and freezes over completely, the runoff season starts in early June and continues to Late September.

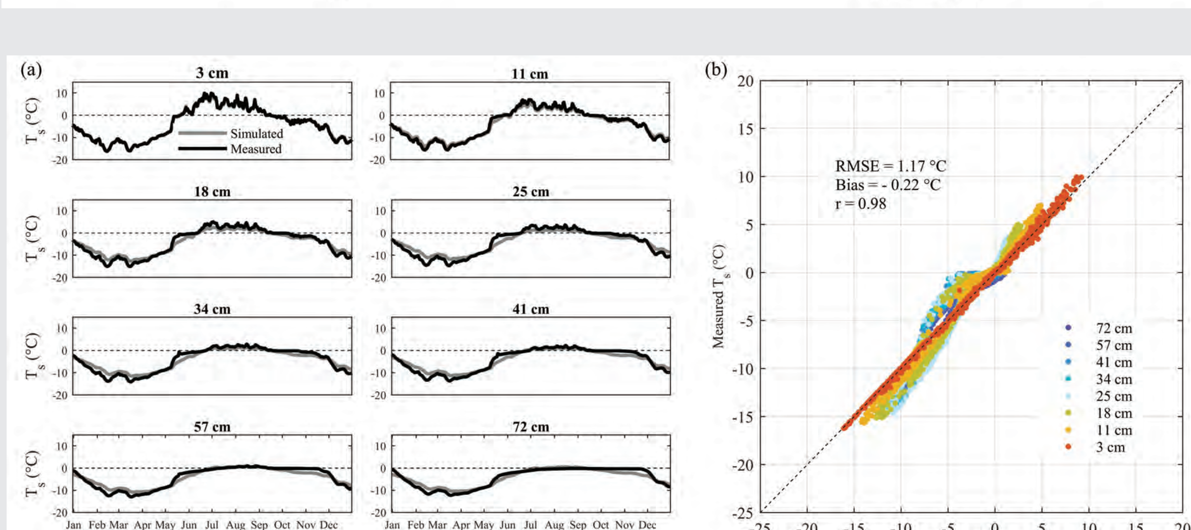
The map shows the location and elevation of the Kuparuk River floodplain and delta. The top right insert shows permafrost distribution in Alaska, and the location of the Kuparuk River watershed (red area). Surface elevations were obtained from the ArcticDEM [Porter et al., 2018], https://www.pgc.umn.edu/data/arcticdem/.

We selected this river system for model validation because it has a long measurement record for discharge (1978 -2017), and 2 years of water temperature measurements (2014-2016).

These lower panels show the location of USGS hydrologic station 15896000 and the river cross section PP' used in our simulations .



River temperature model captures the observed seasonal temperature evolution of the Kuparuk River (R^2 = 0.81).



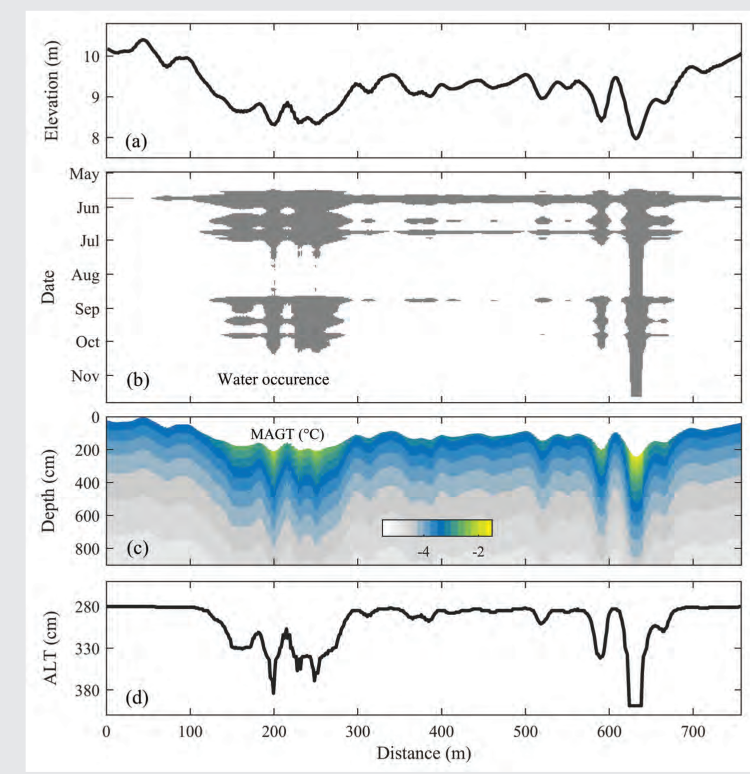
Permafrost model captures seasonal subsurface temperature evolution of a soil profile in comparison to observations at monitored soil profile in Deadhorse (approximately 20km from our study site). (R^2 = 0.96)

Permafrost Patterns Vary Across Channels and Floodplain depending on Flood Duration & Sediment Properties

Variability in inundation determines thermal profile

Simulations investigate the permafrost thermal state for a river cross section close to USGS station 15896000. The river cross section includes two main river channels and floodplain with chute channels in between. Based on the 2 m high-resolution Arctic DEM, inundation over this profile is determined from observed river stage.

Low-lying river stream channels have long flow durations, while basically only the spring snowmelt flood and one larger storm submerge the intermediate floodplain. We simplify and assume the water temperature is homogeneous across the river cross section. Compared with the outer floodplain, the river channels had much higher mean annual ground temperature (MAGT). MAGT also increased from the channel edges to the middle of the river. As a consequence, the active layer beneath the riverbed can reach about 400 cm, which is about 120 cm deeper than the places without river inundation (280 cm). The increase of ALT in the floodplain under a short duration spring flood can be ~20 cm.

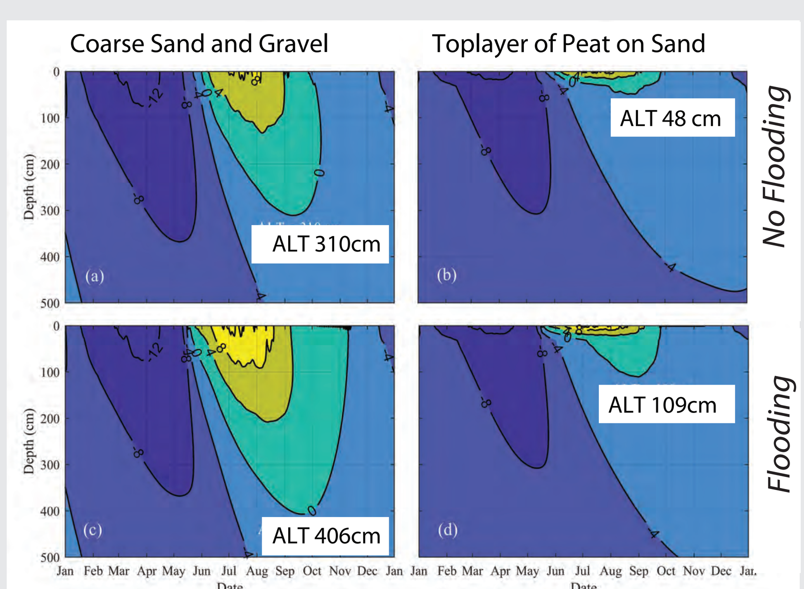


Permafrost thermal state along a river cross section (all conditions are set for 2015). (a) X-section through the floodplain from ARCTICDEM; (b) Inundation occurrences over the spring-sumer and early fall; (c) Simulated mean annual ground temperature MAGT; (d) Simulated active layer thickness ALT. Note the thaw bulbs under the most active channels and differences in active layer depths in small chute channels.

Active channel bed of Kuparuk river

Vegetated floodplain, Kuparuk river

Photos courtesy Josh Koch USGS (June 12, 2013).

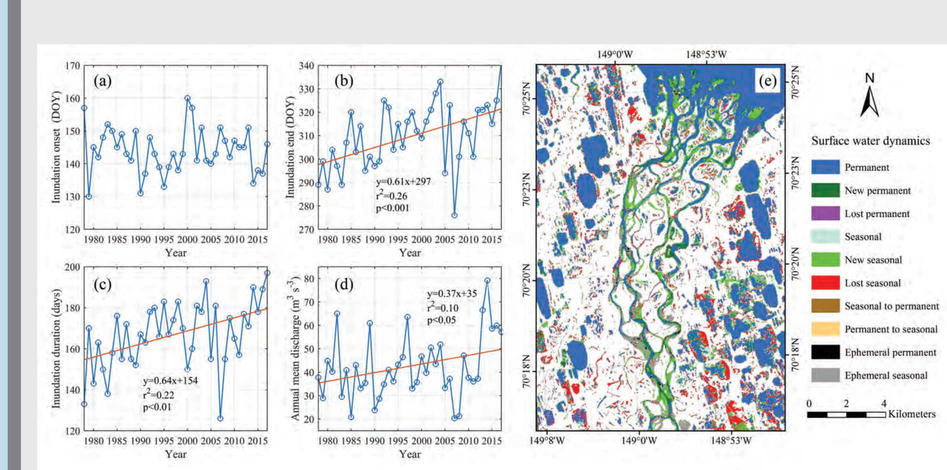


The importance of sedimentary characteristics of channelbed and floodplain deposits

To account for varying floodplain stratigraphy we simulated thermal state in the floodplain with deposits set as end-members of "coarse sand and gravel", versus "sand and gravel deposits with a top peat layer of 30 cm". Coarse sand -dominated profiles respond much more quickly to thermal input due to river inundation. With standing water, ALT in a sand/gravel riverbed increases from 310 cm to 406 cm. Whereas in the profile with a 30 cm peat and organic matter rich top layer, ALT is only 48 cm, remarkably close to the region-wide ALT estimations in Kuparuk River Basin. Under flooding, the active layer underlying such a peat-capped profile increases to 109 cm.

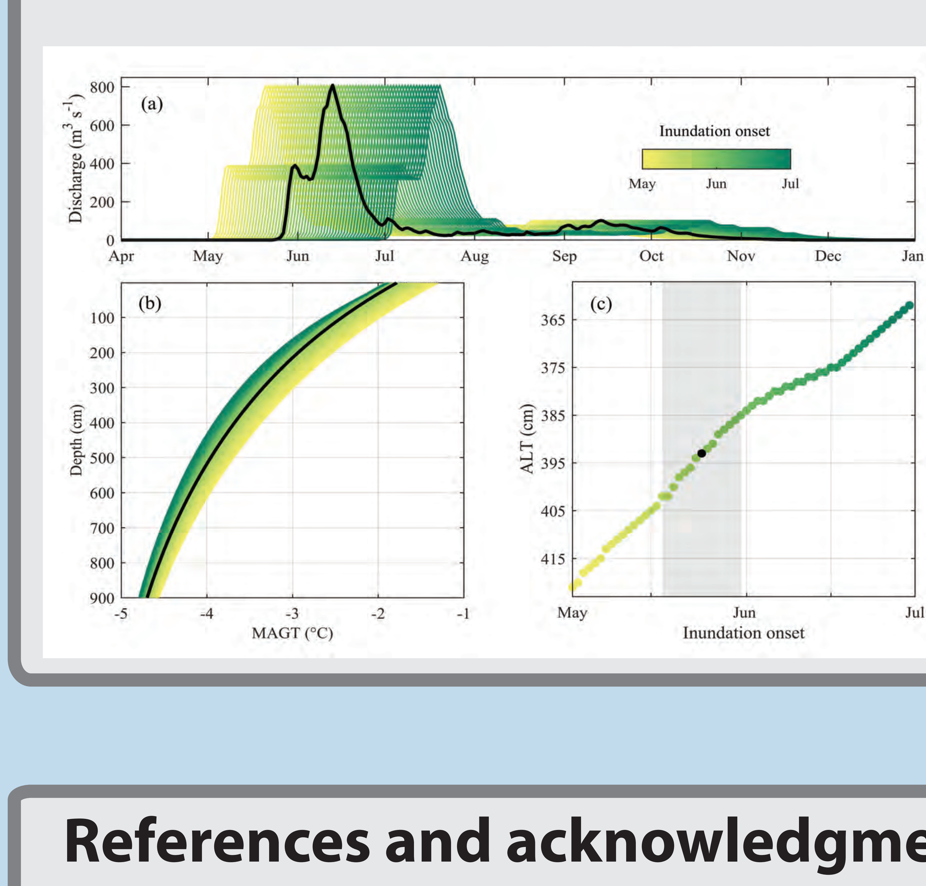
Such different thaw bulbs responses to river inundation in the bare sand and gravel-dominated channel beds and organic-capped floodplain or stream profiles were clearly distinguished by the ground penetrating radar measurements. Due to the relatively higher thermal conductivity, permafrost underlying the coarse-grained deposits is more sensitive to river inundation, whereas peat layers in floodplains provide an insulating effect to warm floodwater effects due to its lower thermal conductivity.

A shift in timing of river flooding rapidly deepens seasonal active layer in floodplains



Inundation timing and discharge can be assessed based on the longterm hydrological observations, as well as the satellite-based water bodies dynamics in the downstream stretch of the Kuparuk River.

On average, river inundation started on 25 May (DOY 144±7), and ended on 7 November (DOY 310±14) over 1978-2017. Inundation onset in the 21st century became earlier (4.68 days decade^{-1}) although no statistically significant change since 1978 is found due to large variability, which is typical in Arctic river systems. The runoff season ended later with a rate of 6.06 days decade^{-1}. Thus, inundation duration became longer at a rate of 6.45 days decade^{-1}.



Experiments run the same discharge at varying timing. The simulations show the profound impact of earlier flood arrival, resulting in significant warming and active layer deepening. This is especially true for early arrival of the freshet, less impactful for a lengthening of the season.

References and acknowledgments

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