# Topographic Signature of Climate Change:

*Insights into climatic controls on landscape evolution under permafrost and non-permafrost environments*

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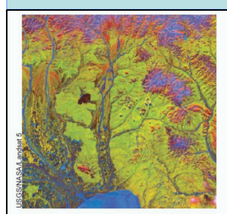
## Problem statement:

The Climate gradient across the deglaciated North American continental landscape has been a major control on the trajectory of landscape evolution following the Last Glacial Maximum (LGM) (~19-25 ka BP). Following deglaciation, landscapes in the Arctic and subarctic regions have been subject to climatic conditions favoring the development and/or preservation of permafrost. In more southerly latitudes, warmer conditions have favored non-permafrost conditions. A comparison of formerly glaciated landscapes in both permafrost and non-permafrost settings offers a unique natural experiment to explore the influence of climate on landscape evolution. Additionally, by comparing formerly glaciated landscapes under both permafrost and non-permafrost conditions to landscapes never having undergone glaciation, it may be possible to identify unique signatures of glaciation on hillslope morphology and processes. After glaciers retreated, newly exposed landscapes exposed to both fluvial and hillslope mass wasting processes, and the relative balance and influence of these processes on landscape evolution varied depending on Holocene climatic conditions (e.g., permafrost versus non-permaforst environments).

Using analysis of high resolution Digital Elevation Model (DEM ~ 1m) data, we show that the topographic denudation on these landscapes over the past Holocene has imprinted a unique climatic signature. Major differences are observed in landscape regimes and regime transitions. These differences are quantified mainly by introducing a new index, Normalized Directed Distance for Relief (NDDR), that treats the landscape relief differences and successfully identify the climate induced landscape responses.

Previously glaciated permafrost present (PP) landscapes are primarily characterized by narrow divergent hilltops (NDDR < 0.3), longer convergent flow paths (~500-1000 m) on hillslopes, and abrupt hillslope to fluvial transitions (< 100 m). Previously glaciated permafrost free (PF) landscapes are characterized by relatively large divergent hillslopes (0.3 ≤ NDDR ≤ 0.9), moderately long convergent flowpaths (400-500 m), and transition from hillslope to fluvial channels through longer networks hollows (200-300 m). We demonstrate our findings using high resolution lidar datasets obtained for Trail Valley, Mackenzie River, Canada (TVC); Brooks Range, North Slope, Alaska (NSBR); Tenderfoot Creek (TFC), Flathead, Montana (FHL), and West Branch Pleasant, Maine (WBPR), USA that were previously occupied by the North American Laurentide Ice Sheet and Brooks Range glaciers. South Fork Eel River (NDDR > 0.9), California is used a representative temperate non-glaciated basin.

Our results suggest, that in landscapes on the north side of the Laurentide ice sheet where permafrost has been present since deglaciation, periglacial landsurface processes such as freeze–thaw driven solifluction process and geomorphic disturbances (active layer detachment, frost heave, etc.) limited the development of channel networks and helped to preserve signatures of glaciation on hillslopes. By contrast, the permafrost restricted southern latitudes display fluvial networks have more fully developed but the hillslopes appear to retain some signature of prior glaciation. Finally, we can now test different hypotheses on many possible future trajectories of landscape evolutions under different climate change scenarios.



Complex patterns of water flow paths, like those feeding Chaunskaya Bay, Siberia, are due to interactions between topographic and hydrologic processes. A new technique to analyze watershed flows has improved the ability to detect regions with different dominant geomorphic processes.

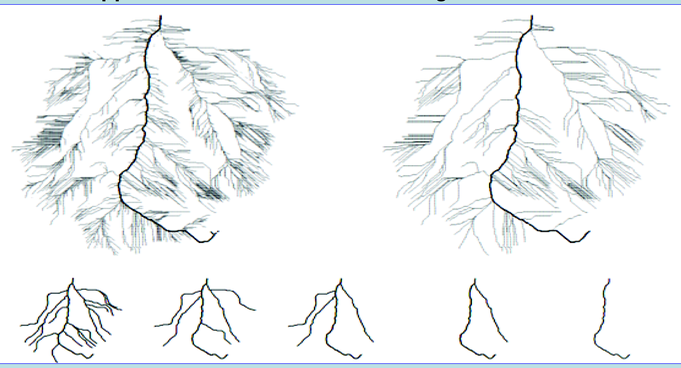
**New watershed classification based on distance to the drainage divide**

Models of watershed behavior are beginning to incorporate lidar (light detection and ranging) topography measurements with resolutions of the order of 1 square meter, but this increase in the availability of high-quality data is outpacing the ability to make the best use of them. At issue is the conceptual lens through which the data are analyzed, particularly when investigating hydrologic behavior at different scales. Scaling parameters are used to break down the masses of data into groupings that fit within certain constraints that can then be analyzed for trends, and watershed research has traditionally used either stream order—a measure based around how many tributaries a body of water has—or the upstream catchment area to make these divisions.

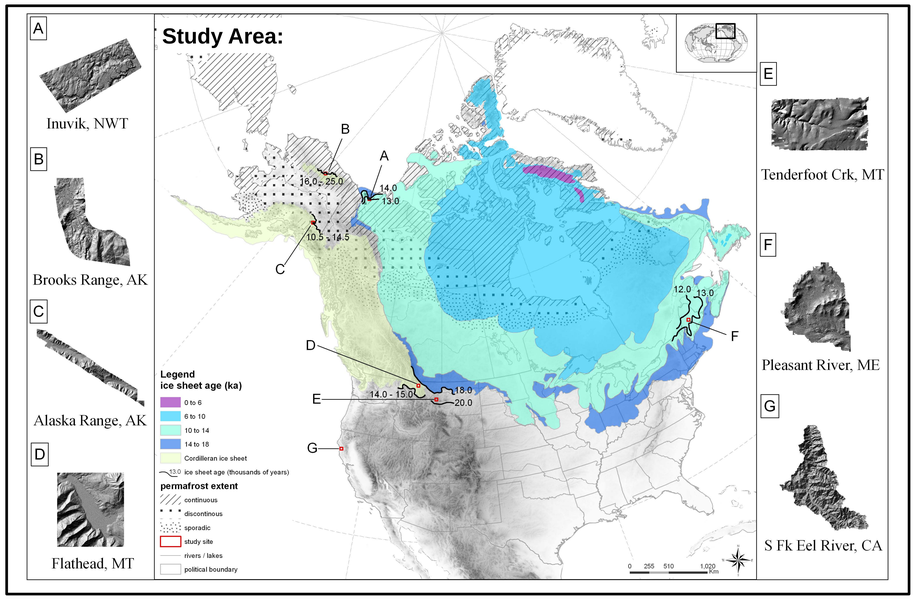
To best make use of the available high-resolution topography data, *Gangodagamage et al.* propose a new scaling parameter based on what the authors refer to as the "directed distance from the divide." The technique involves calculating, for each point in a watershed, the longest distance from that point to a drainage divide, taking into account variations in topography and recognizing that water only flows downhill. When two of these paths converge, the shorter is treated as a tributary to the longer, with this process being repeated until the entire watershed culminates in one major river. From these calculations the watershed can be broken down and analyzed using ensemble statistics based on flow paths of different lengths.

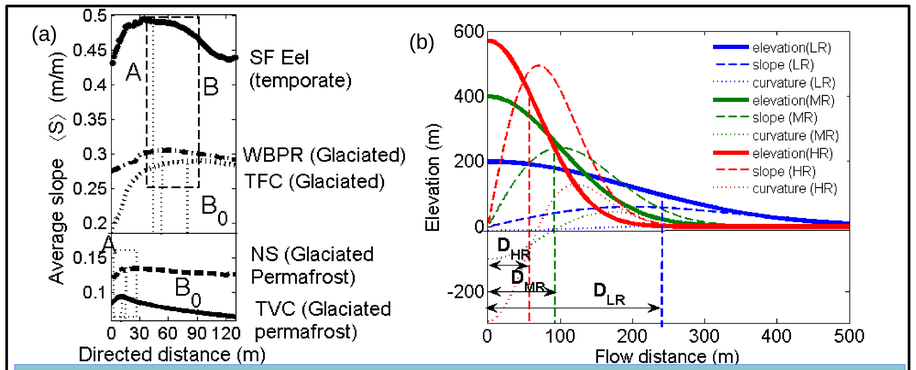
In addition to their theoretical investigation of the technique, the authors analyzed a watershed in Mendocino County, California, at three different spatial scales, finding that directed distance from the divide provides new information, more clearly delineating transitions in geomorphic process regimes relative to other common scaling parameters. (*Water Resources Research*, doi:10.1029/2010WR009252, 2011) —CS

## An innovative approach to understand the changes in the Arctic Landscape

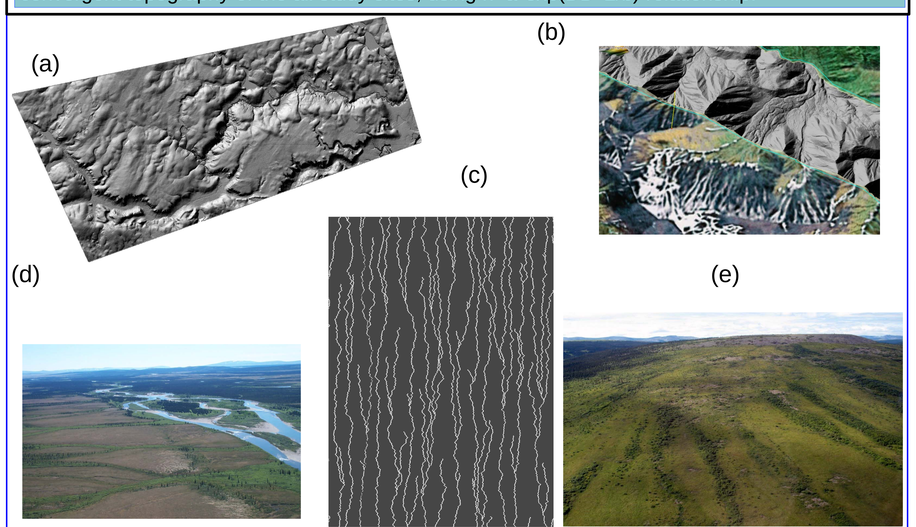


Directed Distance (DD) (distance measured from ridge lines) as a scale parameter covers every part of the landscape from hillslope to flow-tracks to fluvial networks. This seamless scale parameter is a powerful tool to capture landscape dynamic interactions with the external forcing systems such as climate and other landscape disturbances.



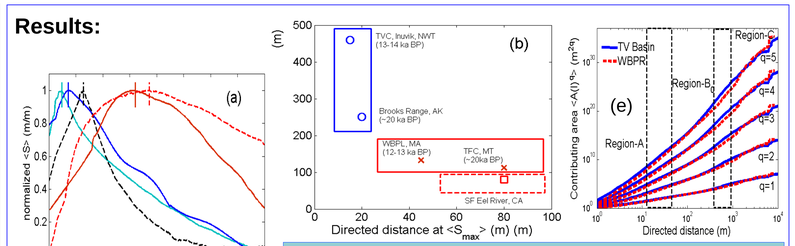




(a) Slope as a function of DD, (b) Elevation profiles, h, were generated for slopes ranging from 0.05 to 0.8 m/m covering the peak slopes ($S_{max}$) at the transition from divergent (region-A) to convergent topography of the all study sites, using h=a*exp(DD^2/b) relationship.

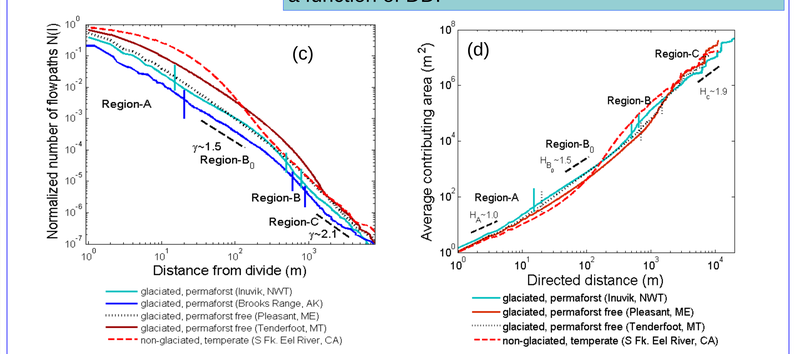



(a) LiDAR topography for TV basin, (b) Immature surficial flow-paths in discontinuous permafrost basin in Denali, Alaska, ( c) simulated Scheidegger type random network flowpaths, (e) The flow convergence of the simulated network agrees with the observed flow convergence of the Study sites (region $B_0$).

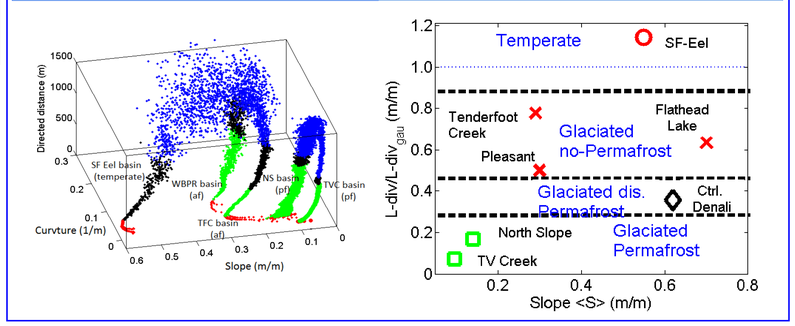
## Results:




(a) Normalized slope (<S>) as a function of DD. (b) $DD=67*S^{-0.83}$ is used to predict the DD at $S_{max}$ for previously glaciated basins, (c) Normalized N(*l*) as a function of DD, (d) contributing area as a function of DD, (e) higher order moments of contribution area as a function of DD.




(a) The slope-curvature-DD relationship for TVC basin, NSBR basin, TFC basin, and WBPR basin. Previously glaciated permafrost basins shows shortest dynamic range for the curvature for their observed low relief landscapes; For, the previously glaciated PF in higher relief landscapes showed increased dynamic range in curvature. The highest dynamic range in curvature is shown by the temperate basin SF Eel River.
(b) DD at the regime transition was predicted by h=a exp ($DD^2/2$) and the predicted distance is used to normalized the observed DD at $S_{max}$ for their relief (NDDR). NDDR and slope plot can differentiate previously glaciated PP, PF and Temperate landscapes.




## Discussion and Conclusions:

Based on our overall classification scheme introduced in this work, we classify the previously glaciated PP landscapes, previously glaciated PF landscapes, and temperate landscape based on their topographic attributes. It is important to further explore how a basins like TVC or NSBR evolve, if the thermally sensitive permafrost retreated due to the changing climate in next 100 years. Do these landscapes follow the evolution trajectories that have shown by WBPR or TFC or do these landscapes follow entirely different landscapes evolution trajectories because these landscapes have different initial and boundary conditions? Do PP landscapes evolve in geological time scales or engineering time scales? Does the final state of these trajectories similar to temperate landscape like SF Eel River. It is also important to test those hypotheses using landscape evolution model by changing their climate scenarios, initial conditions, and relate those finding to our landscape evolution mechanistic equations.

**References:**
C Gangodagamage, Belmond, P. , Fourfoula-Georgiou, E. (2011), wrr, Revisiting river network laws: new scaling consideration in river basins
C. Gangodagamage, Rowland, J. C. , Prancevic, J., Brumby, S., Wilson, C.J., Marsh, P., and Crosby, B. T. (2011) JGR-earth surface, Topographic Signature of Climate Change- insights into climatic controls on landscape evolution under permafrost and non-permafrost environments (in submision)

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