Studying drivers of thermo-erosional gully development based on in-situ measurements, remote sensing data, and modeling

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Thermo-erosional valleys and gullies are widespread and important landscape components in some regions with ice-rich permafrost (Morgenstern et al. 2021). With accelerated arctic warming, channelization and erosion are expected to increase in permafrost regions (e.g., Chartrand et al. 2023). The resulting gully networks not only impact in-situ ground-ice loss through thermo-erosion, but also have far-reaching consequences through changing drainage pathways, modifying the local hydrology as well as sediment, nutrient, carbon, and contaminant fluxes and impacting ecosystems at catchment scale. Only few studies exist that conducted detailed research on thermo-erosional gully development (e.g., Fortier et al. 2007; Godin et al. 2012). However, the underlying process interactions defining incision rates and gully network expansion are complex due to spatially and temporally varying feedback mechanisms and likely are regionally variable. This leads to a lack of predictive tools for future thermo-erosional gully development (Rowland 2023).

In our study, we analyse the thermo-hydrodynamic conditions at two example gullies using in-situ measurements, remote sensing data and modeling at very high spatial resolution. The overall aim is to study driving forces and process interactions impacting further gully deepening or talik formation as well as network expansion in these example settings using permafrost modeling. In particular, we analyse the influence of topography, snow cover, runoff/moisture accumulation, ground ice variation as well as sediment accumulation versus erosion at the gully base. Here we present the analysis of our field data, which will feed into parametrising and validating simulations using the permafrost model CryoGrid.

The two thermo-erosional gully sites are located in West Alaska on the Baldwin Peninsula (BAP) and the Central Seward Peninsula (CSP) in ice-rich permafrost settings, as indicated by ice wedge polygons visible from satellite imagery (Figure 1). BAP is a coastal gully site, where the gully incises more than 10 meters into the surrounding terrain. The gully at CSP was formed following lake drainage and exhibits an incision in the range of one meter (Figure 1a).

At both gully sites, we performed ground temperature, topography (dGPS), active layer thickness (ALT), UAV and LiDAR Backpack surveys. Furthermore, we installed temperature sensors along two transects (T1 and T2), measuring temperature at 15 to 30 min intervals from August 2022 to September 2023. Especially at BAP, the two transects represent different settings where T1 crosses the very upper gully part resembling a shallow water track. Further downstream, the gully gradient makes a step change and levels-out at a deeply incised part with sediment accumulating at the gully center of T2.

Snow cover duration differs significantly across the gullies (Figure 1). During thaw season, snow remains predominantly in snow drifts within the gully and on eastern gully slopes. In contrast, autumn snow layer build-up is delayed in the gully where soil moisture is increased or water is flowing. All this is reflected in the soil surface temperature measurements and is displayed as freezing and thawing degree days (FDD and TDD) in Figure 1b. At all transects, the FDD remain at the highest temperatures at the gully base. In BAP T2, the temperature stays close to the freezing point for the whole winter, whereas in summer the TDD remains comparatively low due to the extended snow cover and snow melt duration. Despite the lower summer temperatures, the ALT exceeds by far the values measured at the other locations. This highlights the complex interactions of snow cover, snowmelt and runoff/moisture accumulation.

In conclusion, the data measured at the two gully sites deliver important insights into the thermo-hydrological processes required to simulate gully deepening driven by the seasonally varying temperature and moisture regimes at the different gully sections. Furthermore, the BAP site proves to be a good test case for modeling the interaction of water tracks, moisture accumulation and gully network expansion along ice wedge polygons.

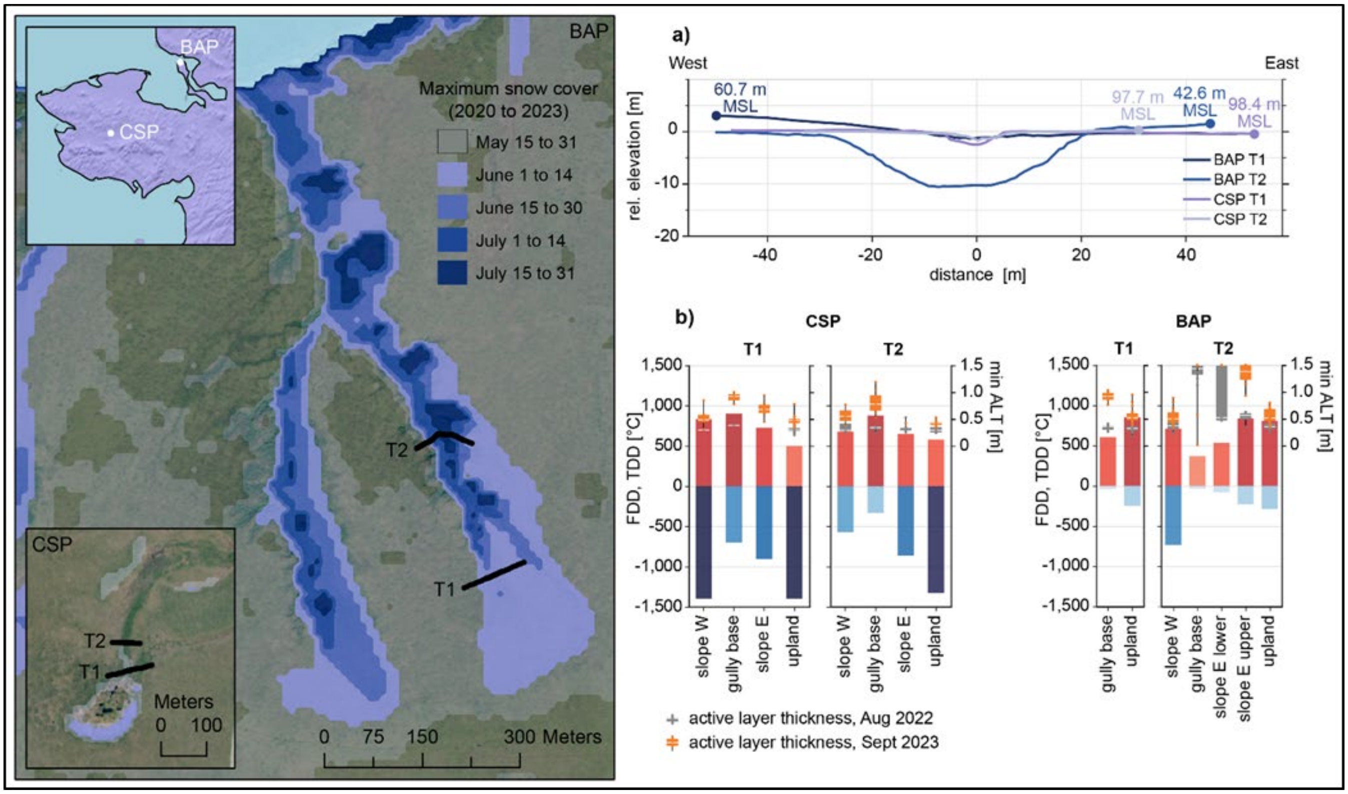

Figure 1. Left: Study site and gully transect locations (T1 and T2) on the Baldwin Peninsula (BAP) and the Central Seward Peninsula (CSP). The blue shading displays the significantly varying snow cover duration along the gully. It was extracted from Sentinel-2 derived NDSI, including imagery from the 2020 to 2023 spring seasons. (Background: Alaska High Resolution Imagery through https://geoportal.alaska.gov/ and Natural Earth hillshade). Right: a) dGPS measurements along the transects, with BAP T2 being significantly deeper incised. b) Annual freezing and thawing degree days (FDD and TDD) derived from soil surface temperature measurements along the four gully transects using 3 to 5 iButton temperature loggers per transect. For all transects the gully base exhibits the highest FDD, with BAP remaining close to the freezing point. In accordance, the active layer thickness (ALT), displayed as boxplots, exceeds the maximum measurable thickness of 1.5 m at BAP T2.

References

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