Interpreting and quantifying temperature-derived thaw metrics as indicators of permafrost change

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Motivation

Ground temperature is widely used to monitor the condition and change of permafrost. Long-term changes to permafrost are commonly described using mean annual ground temperature (MAGT) measured near the depth of zero annual amplitude (DZAA). As permafrost temperatures approach the 0°C, warming rates are reduced by latent heat (a lot of the energy is used to transition from the ice to liquid water, rather than increasing the temperature).

What additional information can we capture from existing thermal monitoring data?

This is important for monitoring because it introduces an extra interpretation step, and can make permafrost change undetectable using MAGT trends. Measuring change at a single depth is useful to simplify permafrost change in a borehole to a single statistic. However, doing so neglects much of the collected data, and the effect of sensor depth on reported trends has not been quantified.

With this study we aim to: (1) Quantify the effect of MAGT sensor depth on observed warming rates. (2) Evaluate how well existing and novel metrics reflect heat gain in permafrost using simulated observations. (3) Recommend a parsimonious set of metrics for future use.

Methods

We use a one dimensional heat transfer model (FreeThaw1d) to run an ensemble of simulations using different ground properties, ice contents, and meteorological scenarios to simulate a variety of permafrost environments. Meteorological data from the ERA5 reanalysis was used to drive the simulation at the surface. Fixed offsets were added to simulate latitudinal temperature variability and future warming was simulated by adding a warming trend based on the SSP2-4.5 scenario (climatedata.ca).

Simulations allow us to explore permafrost change systematically and long-term.

Evaluating metrics as indicators of thaw

For each of the temperature-derived metrics in Figure 1, we perform a qualitative assessment to evaluate what additional information can be obtained. We also perform a quantitative analysis (Figure 3) to determine how reliably each metric corresponds to changes in borehole heat content.

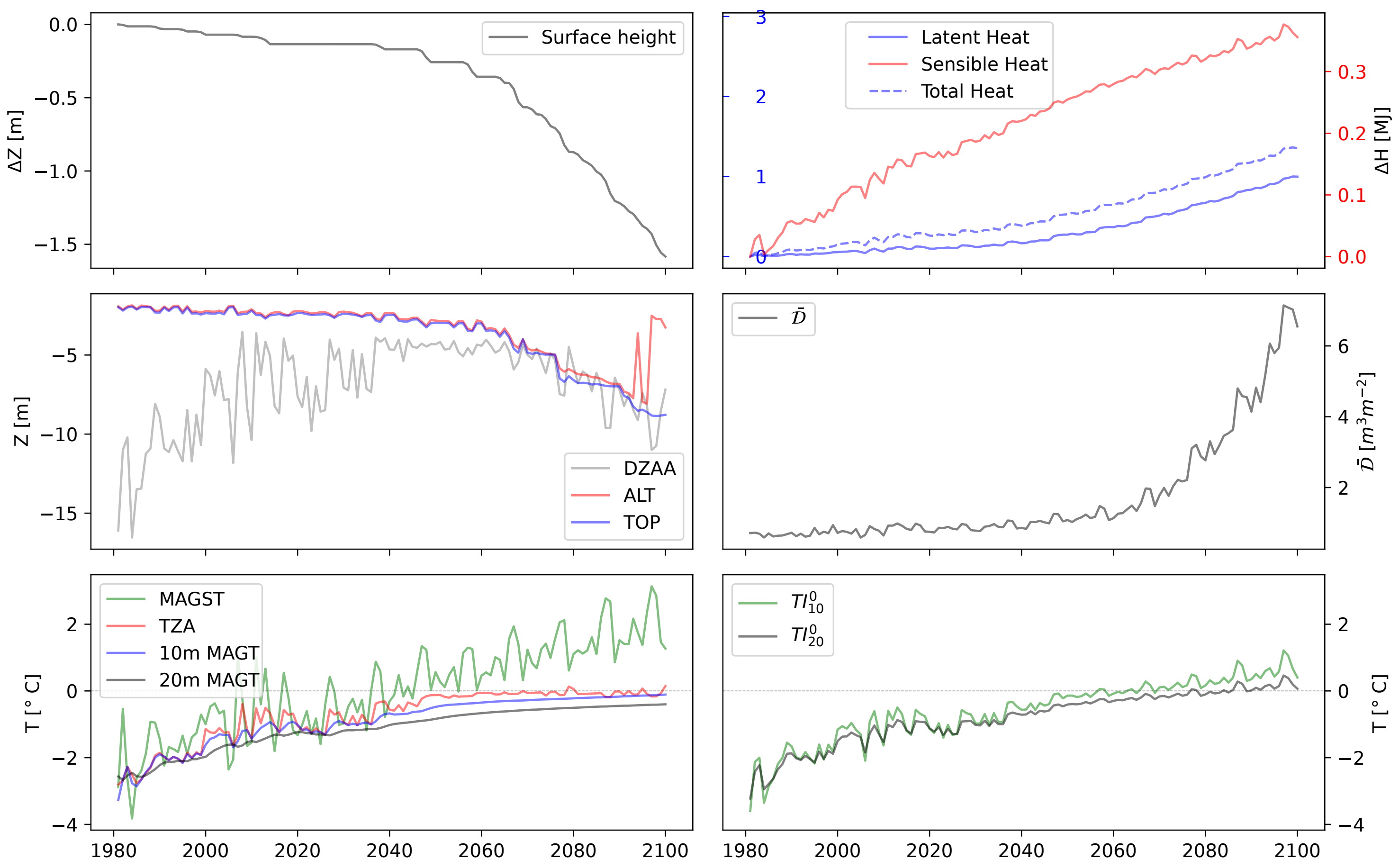
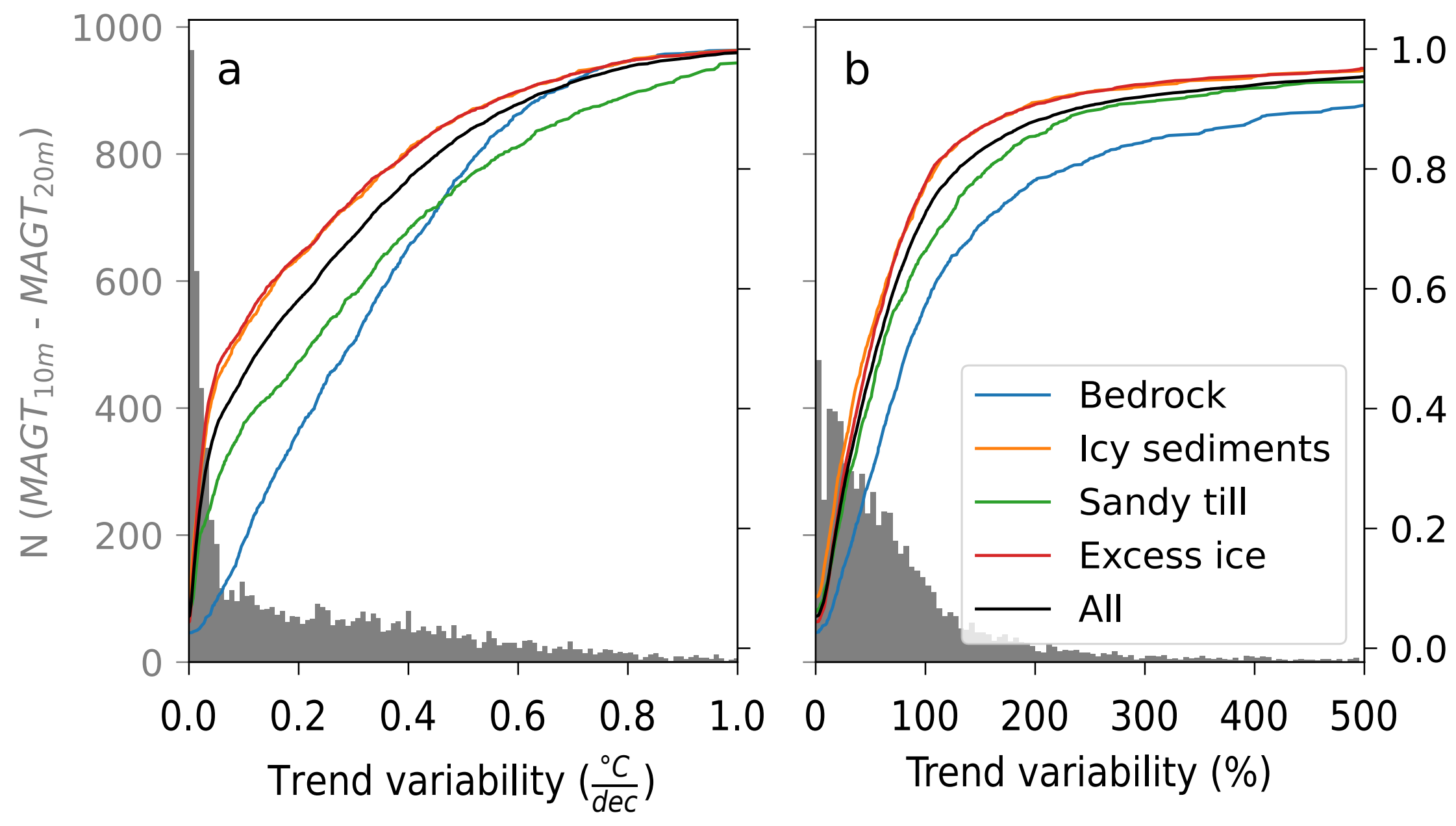


__Figure 1:__ Results for one of the 120-year simulations: a warm, ice-rich soil column. Upper panels show the evolution of simulation-derived system properties such as soil subsidence and heat content. The remaining panels show selected metrics. Plots such as these are used to qualitatively select a parsimonius set of metrics which do not duplicate information (i.e. exhibit a similar trend as one or more other metrics) and which are most consistent as indicators of column heat content.

__Figure 2:__ Dependence of MAGT warming rates on sensor positioning. If trends are calculated for rolling 10-year trend windows across all simulations and for depths between 10 m and 20 m, we find noticeable differences in both (a) absolute differences and (b) relative differences. In both cases, variability is greater in ground types with lower moisture contents.



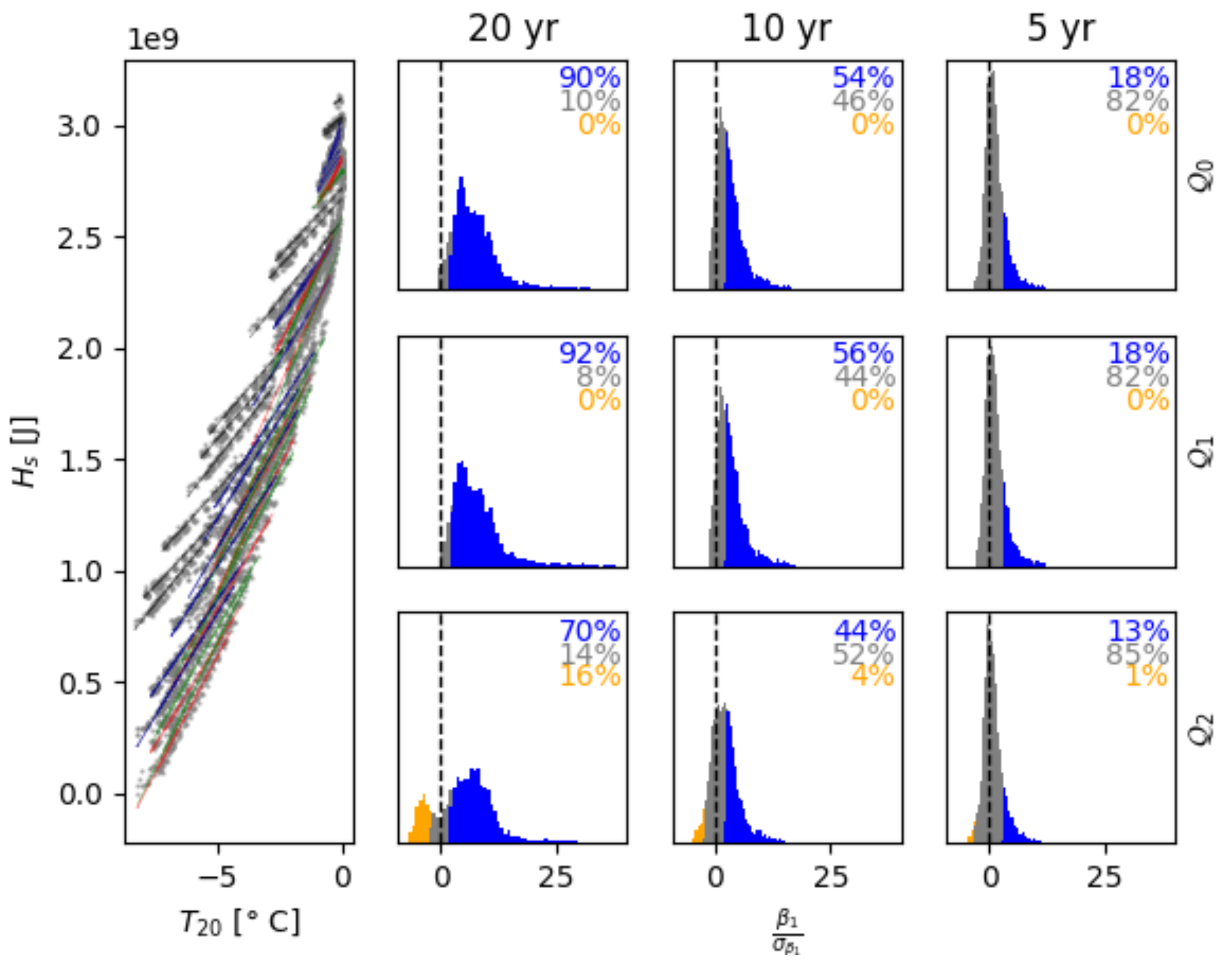


Figure 3: *Example analysis of how a metric (MAGT at 20 m) performs as an indicator of total column sensible heat (H_s) for different observation lengths and levels of sensor quality. Q_0 represents original simulation output while Q1 and Q_2 represent* excellent *and* typical *monitoring systems with added noise, bias, and drift. X-axis represents the correlation coefficient normalized by standard error. Histogram bars and percentanges are colour-coded to indicate positively significant (blue), negatively significant (orange) and non-significant (grey) trends. Left panel shows scatterplot of MAGT against H_s for individual 120-year simulations using Q_0 data.*

MAGT: *mean annual ground temperature*. A widely used and well-documented metric, it is susceptible to periods of very little change. The magnitude of trends is also affected by observation depth (Figure 2), ground material, and temperature (Figure 1).

MAGST: *mean annual ground surface temperature*. Treating MAGST as a proxy for permafrost change has some conceptual challenges because changes in the ground will lag changes at the surface. However, when averaged over longer time periods, the impact of the time lag is reduced. Further, MAGST trends are not so strongly impacted by latent heat (Figure 1). This means it can act as a benchmark for deeper temperature signals: an increasing trend in the MAGST - MAGT difference is indicative of increased latent heat trends while warming at the deeper observation remains isothermal.

TI: The *thermal integral* describes a depth-integrated average borehole temperature. The influence of temperature trends from higher in the borehole means that while the average warming rate of TI may be reduced by latent heat, these effects are somewhat buffered making it less likely to produce an undetectable trend. However, this comes at the cost of greater interannual variability, which may mean longer temporal windows are needed to produce

DZAA: The *depth of zero-annual amplitude* provides additional information about latent heat but is nuanced: change does not correspond linearly to latent heat. The DZAA reflects changes in the annual range of liquid water content, vertically integrated from the surface downward. Generally, an increase in DZAA will correspond to an increase in borehole moisture content even if it isn't linear. However, the metric only responds to changes above DZAA, it requires longer datasets to compensate for greater noise, and it can change direction in response to late-stage warming (Figure 1).

ALT and TOP: The *active layer thickness* and *top of permafrost* are generally similar, but diverge in late-stage warming as a talik develops. Thermal estimation of ALT becomes noisy during this time and the trend eventually reverses in response to warming (Figure 1) so we find TOP to be more interpretable.

TZA: *Annual ground temperature at the dynamic depth of zero-amplitude*. In simulations with ice, this metric is the first to reach the melting point because its position migrates upwards as phase change takes place. Although this can be useful to distinguish phases of permafrost behaviour, it makes TZA less useful as a metric because the challenges caused by latent heat occur sooner.

$\bar{D}$: *thaw-depth duration* is a depth- and time-integrated measure of how much and how long the ground above permafrost is unfrozen. However it behaves similarly to the active layer thickness and top of permafrost (Figure 1) and provides limited additional benefits.

Conclusions

- Additional temperature-derived metrics provide context and new information that can support interpretation of MAGT trends.
- TOP, DZAA, MAGT, and TI are recommended as a parsimonius set of metrics
- Trend magnitude is strongly context-dependent: ground material, observation depth, and thermal state can all significantly affect observed rates of change. For ALT and DZAA, these can even affect the direction (sign) of the trend in response to warming.

This project was enabled in part by support provided by Westgrid (westgrid.ca) and the Digital Research Alliance of Canada (alliancecan.ca).

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