Permafrost

Identification

1. Description

This indicator shows trends in Alaskan permafrost temperature based on borehole measurements. Permafrost is defined as rock or soil and included ice that remains at or below 0°C (32°F) for two or more years and usually occurs beneath the active layer, which annually freezes and thaws (IPCC, 2019). The continuity and classification of permafrost coverage changes latitudinally and is dependent on land cover type, slope, and other local environmental characteristics. Permafrost is particularly sensitive to changing climatic conditions, notably rising surface air temperatures and changing snow regimes (IPCC, 2019; Smith et al., 2010). At depths of 10 to 200 meters (32.8 to 656.2 feet), the permafrost temperature regime is a highly sensitive indicator of long-term climatic variability. This is because interannual temperature ranges decrease significantly with increases in depth, allowing for the observation of precise, decadal temperature variation (Yershov, 1998). Changing permafrost temperature can amplify global climate change, as thawed sediments unlock and release soil organic carbon—including methane, which has a high global warming potential—into the carbon cycle (Schaefer et al., 2014). Other consequences of permafrost thaw include but are not limited to building foundation failure and decreased infrastructure stability, as well as decreases in slope stability that can lead to destabilized mountain structure and slope failure. As a subsurface phenomenon, the temporal changes and spatial distribution of permafrost cannot easily be observed, unlike glaciers and polar sea ice (IPCC, 2019). However, the connection between permafrost temperature and climate change can be determined through a reproducible data collection regime at specific borehole sites throughout Alaska.

Components of this indicator include:

- Time series of soil temperatures in interior and northern Alaska boreholes, from 1978 to present (Figure 1).
- A map of borehole sites with accompanying temperature trend visualization (Figure 2).

2. Revision History

April 2021: Indicator published.

Data Sources

3. Data Sources

Both figures use yearly observational data provided by Dr. Vladimir E. Romanovsky and the Permafrost Laboratory in the Geophysical Institute of the University of Alaska Fairbanks. Data are collected annually via boreholes across Alaska. The best way to characterize temporal trends in permafrost temperature is to collect consistent, long-term observations at designated borehole stations (Romanovsky et al., 2010). Borehole data continue to be measured by the University of Alaska Fairbanks.

4. Data Availability

Borehole temperature data are publicly available from the Permafrost Laboratory of the University of Alaska Fairbanks, along with corresponding metadata, at: https://permafrost.gi.alaska.edu/sites_map. Users can learn more about the methodology at: https://permafrost.gi.alaska.edu/content/methods. More information about the work of the Permafrost Laboratory is detailed on their website: https://permafrost.gi.alaska.edu/about.

Some of the data used in this indicator are also publicly available online at the NSF Arctic Data Center at: https://arcticdata.io/catalog/data. Additionally, borehole data on a global scale are publicly available from the Global Terrestrial Network for Permafrost (GTN-P) at: https://gtnp.arcticportal.org. The GTN-P is an international program tasked with monitoring permafrost. It was developed by the International Permafrost Association under the Global Climate Observing System and the Global Terrestrial Observing Network in 1999. Its long-term goal is to obtain a complete view of the trends, spatial composition, and variability of changes in permafrost structure and temperature (Biskaborn et al., 2015, 2019).

EPA worked directly with Dr. Vladimir E. Romanovsky to obtain a compilation of data for all the specific sites and years covered by this indicator.

Methodology

5. Data Collection

This indicator is based on observational research and measurements by the University of Alaska Fairbanks. Data measurements are divided between two primary study regions: Interior Alaska and Northern Alaska. Data collection periods of record vary by region and by site.

Within the Northern Hemisphere polar region, ground temperatures are being measured in approximately 575 boreholes throughout North America, the Nordic regions, and Russia (Romanovsky et al., 2010)—including more than 100 in Alaska. For many sites, though, the record length is too short, the methods used vary, or data are not complete enough for comparability or long-term trend assessment. Therefore, this indicator focuses on a subset of 15 sites with the longest and most complete data record to characterize trends related to climate. Table TD-1 identifies these sites, their corresponding study regions, and the depth of measurements used in this indicator. The sites selected for this indicator are also consistent with other published permafrost indicators (e.g., Blunden and Arndt, 2019; Romanovsky et al., 2017).

In the interior Alaska study region, the earliest measurement across the eight selected borehole sites is from 1983. In the northern Alaska study region, the earliest measurement across the seven selected borehole sites is from 1978. Both study regions contain data until 2020, with updated data collected on an annual basis. The average number of yearly data points per borehole in interior Alaska is 29.5 (standard deviation = 3.91), and the average number of yearly data points per borehole in northern Alaska is 30.29 (standard deviation = 10.79). At a few sites, data could not be collected in 2020 because of the COVID pandemic.

Borehole sites used in this indicator are established in undisturbed areas and span a wide range of permafrost, climatic, and environmental conditions. The majority of sites are located along or near the International Geosphere-Biosphere Programme Alaskan transect, which runs across the entire state of Alaska from north to south (see Figure 2). Site elevations range from 2.7 to 976.3 meters (9 feet to 3,203 feet) above sea level, with an average of 312.2 meters (standard deviation = 298.3) (1024.3 feet, standard deviation = 978.6).

The manual at: https://permafrost.gi.alaska.edu/sites/default/files/TSP_manual.pdf provides details about measurement. Some boreholes use continuous observations with automated sensors that report with hourly or daily frequency; the standard is every six to eight hours. Others use less frequent, non-automated measurements. Temperature readings at all sites are measured by either a Measurement Research Corporation 107 Temperature Probe or an Onset Computer Corporation StowAway (XTI or Optic) sensor. Sensors are calibrated in the field to ensure accuracy.

Temperature at each site is measured at multiple depths, typically at intervals of 2 meters (6.6 feet). Most of the sites in this study have their shallowest measurement at 6 meters (19.7 feet) below ground level. Differences in the suitability of local conditions between sites necessitates variation of the shallowest measurement depth. The deepest measurements range from 28 to 75 meters (91.9 to 246.1 feet) below ground. Table TD-1 lists the depth selected for long-term trend analysis at each site, based on the approach described in Section 6 below.

Table TD-1. Borehole Locations and Measurement Depths Used for This Indicator

Region	Borehole location	Measurement depth
Interior Alaska	Old Man	15 meters (49 feet)
	Birch Lake	15 meters (49 feet)
	Chandalar Shelf	20 meters (66 feet)
	Coldfoot	26 meters (85 feet)
	College Peat	20 meters (66 feet)
	Livengood	15 meters (49 feet)
	Healy	15 meters (49 feet)
	Gulkana	15 meters (49 feet)
Northern Alaska	Galbraith Lake	20 meters (66 feet)
	Happy Valley	20 meters (66 feet)
	Franklin Bluffs	20 meters (66 feet)
	Kaktovik (ANWR/Barter)	20 meters (66 feet)
	Deadhorse	20 meters (66 feet)
	Barrow 2 (N. Meadow Lake No. 2/NML-2)	16 meters (53 feet)
	West Dock	20 meters (66 feet)

6. Derivation

This indicator is based on measurements that are most representative of annual average conditions in each borehole. Where multiple timestamps are available (in the case of sites with automated temperature sensors), annual averages are used. At each site, one representative depth was chosen for use in this indicator. The most appropriate depth for use is the depth of zero annual amplitude—i.e., the shallowest depth where seasonal variations of ground temperature become negligible. This condition occurs at different depths in different locations, ranging from a few meters in warm, ice-rich permafrost to 20 meters or more in cold permafrost and bedrock (AMAP, 2017). For most of the sites used for this indicator, the selected depth was either 15 or 20 meters (49.2 or 65.6 feet). Measurements from 26 meters (85.3 feet) were used at one site where that was the shallowest measurement available in all years.

The graph in Figure 1 shows the temperature measurements recorded each year at the specified depths. No further calculations or transformations were needed to generate these time series.

The map in Figure 2 shows a long-term rate of temperature change at each site. EPA calculated this rate of change by performing an ordinary least-squares linear regression with the data for each site, then multiplying the regression slope by 10 to derive an average rate of temperature change per decade. The map shows results at each site, with no attempt to generalize or model results over space.

7. Quality Assurance and Quality Control

The University of Alaska Fairbanks conducts quality assurance and quality control (QA/QC) activities prior to data distribution. Key steps include equipment calibration before collecting measurements.

Additionally, sites in disturbed areas or sites that became disturbed (i.e. wildfire, infrastructure changes, etc.) are removed from the analysis to ensure data quality. The indicator does not include sites with data collection methods that differed from the University of Alaska Fairbanks' standardized data collection protocol.

Additional QA/QC procedures for manual measurements are largely unavailable online. Data used in this indicator have been peer-reviewed and published by reputable scientific journals, reports, and other texts.

Analysis

8. Comparability Over Time and Space

For consistency, this indicator examines trends at depths that are selected to be most representative of average conditions throughout the year. Borehole sites do not change location, providing spatial consistency.

Data collection methods may have changed slightly with advancements in probe technology. The University of Alaska Fairbanks, however, has taken careful steps to calibrate and quality-check their equipment before data collection and dissemination (see Section 7). Standardized data collection and QA/QC protocols ensure methods are applied consistently over time and space.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Some borehole sites rely on data collected at depths less than 20 meters (66 feet), which may be subject to notable influence by seasonal or short-term surface temperature changes. Permafrost temperature measurements 20 meters and deeper are not affected by seasonal variation and are therefore considered ideal for identifying long-term trends (Romanovsky et al., 2007).

2. Gaps in the dataset produce an imperfect estimation of potential permafrost temperature trends. The gap around 2003–2004 reflects a period in which the monitoring program and dataset were transition from one research team to another. However, all sites included in this indicator have sufficient data for trend analysis. Sites with larger data gaps (> five years consecutive and seven years overall) have been excluded from the analysis.

3. Due to local environmental characteristics, this collection of sites is not necessarily indicative of all varieties of permafrost and the associated temperature trends. Permafrost is highly variable, and permafrost temperature is linked with multiple environmental factors such as soil type, aspect, and snow cover depth (Smith et al., 2010). Most notably, permafrost in interior Alaska is naturally warmer and less continuous than permafrost in northern Alaska. For these reasons, among others, this indicator focuses more on individual site temperature comparisons over time and less on inter-site comparisons. This variation must be kept in mind when looking at permafrost temperatures at larger regional or pan-Arctic scales.

10. Sources of Uncertainty

A small amount of uncertainty is inherent due to the temperature measurement system at each borehole. However, the measurement methodology used throughout the period of record generally provides an accuracy and precision of 0.1°C (0.18°F) or better (Romanovsky et al., 2010).

Differences in environmental characteristics at specific borehole sites may introduce uncertainty to the indicator, although the broad spatial distribution provides a degree of certainty to the analysis. A diverse collection of sites nearly all trending in the same direction suggests the presence of a broader-scale influence and change that is more than just the result of specific local factors.

Calculating temperature trends when data gaps are present adds a small amount of uncertainty to the indicator.

11. Sources of Variability

Natural year-to-year variations in snowfall, surface temperature, air temperature, and other climate variables may directly influence short-term permafrost temperatures. This indicator looks at longer-term temporal trends with a wide degree of spatial variation, thus reducing the influence of year-to-year variability. Over a longer timeframe, non-climatic factors such as land-use change, anthropogenic disturbance, and wildfire can influence permafrost temperature trends. Borehole sites were chosen to specifically avoid these non-climatic factors, although minor influences are possible.

12. Statistical/Trend Analysis

Figure 2 displays long-term trends based on a least-squares linear regression of annual observations at each borehole site for the site's period of record. The statistical significance of each of these trends was examined based on the p-values of these regressions. Of the 15 sites, all but Livengood and College Peat had a trend that was significant to a 95 percent level ($p < 0.05$).

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