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Trends of Thermal, Wetness, and Vegetative Change in the Circumpolar Arctic

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Dataset Version: 1

Summary

This dataset provides estimates of trends in temperature, moisture, and vegetation changes over the circumpolar Arctic. Time series trends were measured by the Theil-Sen slope and associated p-values for a variety of variables including 2-meter air temperature, precipitation, soil moisture, non-frozen season days, permafrost active layer thickness, snow cover, vapor pressure deficit, land surface water fraction, normalized difference vegetation index (NDVI), and vegetation optical depth. Trends were measured annually and over specific seasons of spring (March to May), summer (June to August), autumn (September to November) and winter (December to February), and for the 1980-2020 and 1997-2020 time periods, depending on the variable and original data availability. Emerging hotspots of change were identified for the same variables and seasons, but only over the 1997-2020 period. In addition, a multivariate ranking was used to create combined hotspot layers to show areas of substantial changes in the thermal environment, moisture, and vegetation; these themes reflect landscape changes considered to be detrimental (e.g., a threat) to ecosystems and human populations. Ancillary files provide the boundaries of study regions, Brown permafrost regions, and a land cover product. The data are provided in cloud optimized GeoTIFF (COG) and shapefile formats.

The high latitudes cover ~20% of Earth's land surface. This region is facing many changes in thermal, moisture and vegetation properties, driven by a warming climate. This dataset holds results from an analysis of remote sensing-informed records of key ecosystem indicators. The results can improve understanding of landscape-level changes measured using non-parametric trend detections and Getis-Ord G_i^* spatial hotspot assessments.

This dataset holds 217 files: 206 cloud optimized GeoTIFFs, 10 shapefiles in compressed Zip archives, and one file in comma separated values (CSV) format.

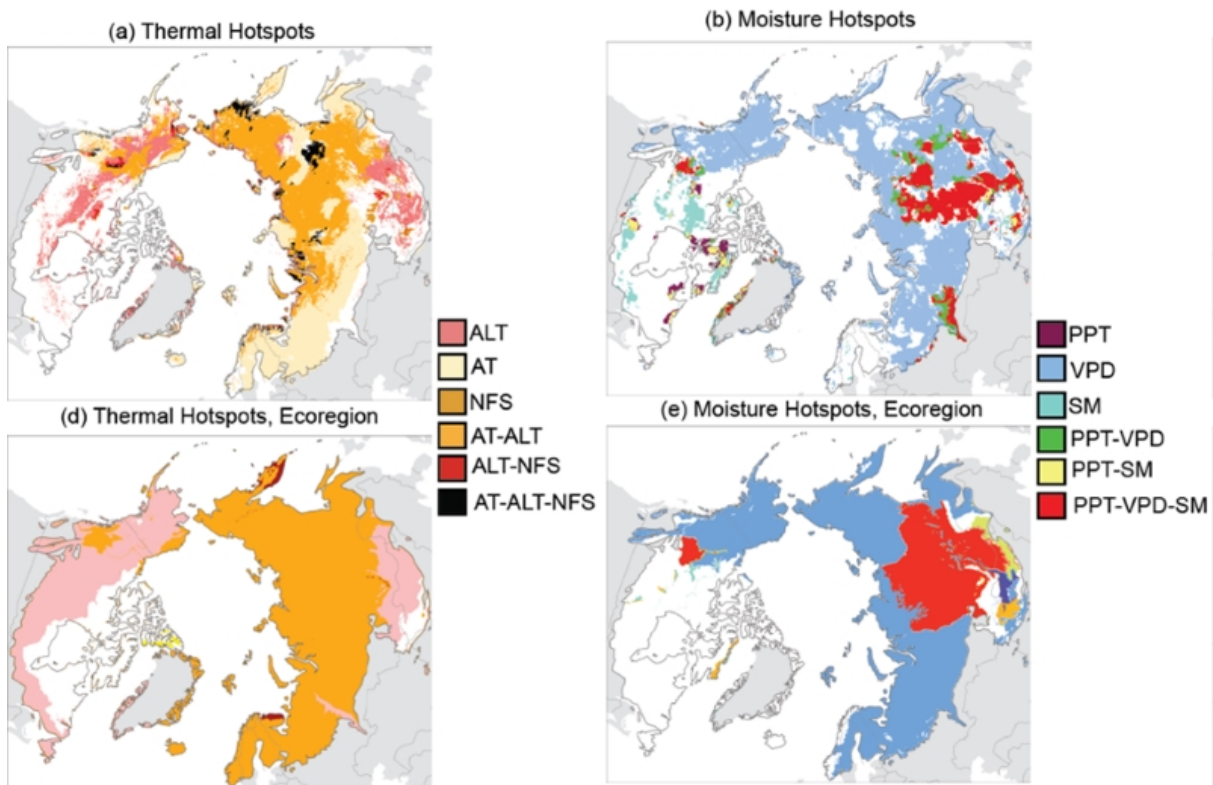


Figure 1. Multivariate change hotspot maps for the 1997 to 2020 period, according to select directional changes in thermal, moisture, and vegetation indicators. Thermal indicator includes: average increase in annual air temperature (AT, degrees C); increase in annual non-frozen season (NFS, days); and increase in annual active layer thickness (ALT, m). Moisture indicator includes: decrease in annual precipitation (PPT, mm); increase in annual vapor pressure deficit (VPD, kPa); and a decrease in annual non-frozen season soil moisture (SM, cm³ cm⁻³). Panels (a) and (b) show identified change based on pixel-level analyses; (d) and (e) show indicator change across individual ecoregions.

Citation

Watts, J.D., S. Potter, B.M. Rogers, A.-M. Virkkala, G. Fiske, K. Arndt, A. Burrell, S. Natali, K. Butler, B. Gerlt, J. Grayson, T.A. Shestakova, J. Du, and Y. Kim. 2023. Trends of Thermal, Wetness, and Vegetative Change in the Circumpolar Arctic. ORNL DAAC, Oak Ridge, Tennessee, USA. <https://doi.org/10.3334/ORNLDAAC/2322>

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1. Dataset Overview

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Project: [ABoVE](#)

The Arctic-Boreal Vulnerability Experiment (ABoVE) is a NASA Terrestrial Ecology Program field campaign being conducted in Alaska and western Canada, for 8 to 10 years, starting in 2015. Research for ABoVE links field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving the analysis, and modeling capabilities needed to understand and predict ecosystem responses to, and societal implications of, climate change in the Arctic and Boreal regions.

Related Publication:

Watts, J.D., S. Potter, B.M. Rogers, A.-M. Virkkala, G.Fiske, K.A. Arndt, A. Burrell, K. Butler, B. Gerlt, J. Grayson, T.A. Shestakova, J. Du, Y. Kim, F.-J. Parmentier, and S.M. Natali. 2024. Regional hotspots of change in northern high latitudes informed by observations from space. *ESS Open Archive*. <https://doi.org/10.22541/au.170497370.03373595/v1>

Related Datasets:

Related data are available on the [ABoVE Project page](#).

Acknowledgements:

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2. Data Characteristics

Spatial Coverage: Circumpolar Arctic

ABoVE Reference Locations

Domain: Core ABoVE

Cells: All "A" cells in the core ABoVE domain

Spatial Resolution: nominally 10 km

Temporal Coverage: 1980-01-01 to 2020-12-31

Temporal Resolution: Single estimates for each of two periods: 1980-2020 and 1997-2020

Study Areas: Latitude and longitude are given in decimal degrees.

Site	Westernmost Longitude	Easternmost Longitude	Northernmost Latitude	Southernmost Latitude
Circumpolar Arctic	-180	180	90	30

Data File Information

This dataset holds 217 files: 206 cloud optimized GeoTIFFs, 10 shapefiles in compressed Zip archives, and one file in comma separated values (CSV) format.

GeoTIFF

The GeoTIFF files include estimates of change trends (Theil-Sen slope), statistical significance of slope estimates (pvalue), and hotspots of change for 12 remotely sensed indicators of change.

The file naming convention for most GeoTIFFs is `<indicator>_<year1>_<year2>_<month1>_<month2>_<metric>.tif`, where

- `<indicator>` = abbreviation for remotely sensed indicator variable (see Table 1).

- <year1> and <year2> = the beginning and ending years, respectively, of the period analyzed.
- <month1> and <month2> = the beginning and ending months, respectively, of the analysis period during the years studied. "1_12", annual period; "3_5", March to May (spring), "6_8", June to August (summer), "9_11", September to November (autumn); and "12_2", December to February (winter).
- <metric> = "slope", "pvalue", or "hotspot" (see Table 2).

Twelve GeoTIFFs hold estimates of hotspots derived from a multivariate ranking of related indicators. The naming convention for these files is 1997_2020_<month1>_<month2>_<theme>_combined_hotspot.tif, where

- <theme> = "moisture", "thermal", or "vegetation"

The file *land_cover.tif* includes the distribution of tundra, boreal forest, boreal wetlands, and grass/shrub covers.

The nominal spatial resolution for the GeoTIFFs is 10,000 m (10 km).

Shapefiles

The shapefiles hold vector polygons of regions within the circumpolar study area. The file naming convention is <region>_shapefile.zip, where <region> =

- "arctic_domain", entire study area;
- "eurasia", Europe and Asia portions of the Arctic; "north_america", North American portion of the Arctic;
- "boreal", circumpolar boreal zone,
- "boreal_ea"; boreal region of Europe and Asia; "boreal_north_america", boreal region of North America;
- "tundra", circumpolar tundra;
- "tundra_eurasia", tundra region of Europe and Asia; "tundra_north_america", tundra region of North America

The *brown_permafrost_shapefile.zip* holds polygons denoting types of permafrost from Brown et al. (2002). Attributes of this file are included in the companion file *Brown_permafrost_attributes.pdf*.

User Note: The coordinate reference system (CRS) varies among the GeoTIFFs and shapefiles. The file *CircumArctic_Trends_Hotspots_file_CRS.csv* lists each file's CRS by EPSG code and proj4 string.

Files with EPSG 3410 are in NSIDC's EASE-Grid. Users should ensure that their spatial data software properly recognizes this EPSG code and/or its proj4 string. Please refer to [EPSG.org](https://epsg.org) or [A Guide to EASE Grids](#) (NSIDC, 2023) for a detailed definition of this CRS. Brodzik et al. (2012) provide more information about the EASE grids. A list of [tools compatible with EASE grids](#) is available from NSIDC.

Companion files

This dataset includes 14 companion files. The text files provide labels for the pixel values for the 1997_2020_<month1>_<month2>_<theme>_combined_hotspot.tif and land_cover.tif files that can be used to build legends for GIS layers. The file *Brown_permafrost_attributes.pdf* holds CRS and attribute information for *brown_permafrost_shapefile.zip*.

Table 1: Remotely sensed indicators of landscape-level change with associated theme.

Abbreviation	Indicator	Units	Source
Thermal theme			
ALT	Active layer thickness, annual maximum	m	Kim et al. (2017, 2021)
nfs	Non-frozen season	d	
tmean	Air temperature 2-m above land surface	degree C	Hall et al. (2001, 2002); Muñoz-Sabater et al. (2021)
Moisture theme			
FW	Percent cover of surface water on land	percent	Du et al. (2017); Jones and Kimball (2021)
ppt	Monthly or annual average precipitation	m	Hall et al. (2001, 2002); Muñoz-Sabater et al. (2021)
SM	Soil moisture (volumetric)	m ³ m ⁻³	
Snow	Percent snow cover	percent	
VPD	Vapor pressure deficit	kPa	
Vegetation theme			
NDVI	Normalized difference vegetation index	1	Pinzon and Tucker (2014)
NTC	Percent cover of non-tree area	percent	Hansen & Song (2018)
TC	Percent cover of surface water on land	percent	
VOD	Vegetation optical depth	1	Moesinger et al. (2020)

Table 2. Description of trend metrics.

Metric	Units	Description
hotspot	1	Emerging hotspot value for years and months analyzed. Values: -3 (99% confidence of cold spot), -2 (95% confidence of cold spot), -1 (90% confidence of cold spot), 0 (no change), +1 (90% confidence of hotspot), +2 (95% confidence of hotspot), +3 (99% confidence of hotspot)
pvalue	1	Statistical significance of Theil-Sans slope

slope	(unit) y^{-1}	Theil-Sen slope for the indicator (Table 1). Magnitude is the unit of the indicator (Table 1) per year. For example, the unit for <i>ALT_*_slope.tif</i> is meters per year ($m\ y^{-1}$).
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Table 3. Definition of pixel values in *1997_2020_<month1>_<month2>_moisture_combined_hotspot.tif*.

Pixel value	Hotspot drivers
1	Precipitation
2	Vapor pressure deficit
3	Soil moisture
4	Precipitation and Vapor pressure deficit
5	Precipitation and Soil moisture
6	Precipitation, Vapor pressure deficit, and Soil moisture

Table 4. Definition of pixel values in *1997_2020_1_12_thermal_combined_hotspot.tif*.

Pixel value	Hotspot drivers
1	Active layer thickness
2	Air temperature
3	Non-frozen season length
4	Active layer thickness and Air temperature
5	Active layer thickness and Non-frozen season length
6	Active layer thickness, Non-frozen season length, and Air Temperature

Table 5. Definition of pixel values in *1997_2020_3_5_thermal_combined_hotspot.tif*, *1997_2020_9_11_thermal_combined_hotspot.tif*, and *1997_2020_12_2_thermal_combined_hotspot.tif*

Pixel value	Hotspot drivers
1	Air temperature
2	Non-frozen season length
3	Air Temperature and Non-frozen season length

Table 6. Definition of pixel values in *1997_2020_<month1>_<month2>_vegetation_combined_hotspot.tif*.

Pixel value	Hotspot drivers
1	Normalized difference vegetation index (NDVI)
2	Vegetation optical depth (VOD)
3	NDVI and VOD

Table 7. Vegetation types in *land_cover.tif*.

Pixel value	Vegetation type
17, 18, 45, 47, 49, 62-64	Boreal forest
65, 60, 61	Boreal wetland
65	Grass/shrub
All other values	Tundra

3. Application and Derivation

These data are useful for examining how specific variables relating to climate, and more specifically thermal, moisture and vegetation have changed over time dating back to 1980 over the circumpolar arctic.

4. Quality Assessment

No quality assessment is provided. See Watts et al. (2024) for details of the associated research.

5. Data Acquisition, Materials, and Methods

Trends in temperature, moisture, and vegetation over the circumpolar Arctic were estimated from remotely sensed data products (Table 8). Data from 12 indicators were aggregated to quantify seasonal and annual trends.

The ERA5 2-m air temperature (tmean), precipitation (ppt) and vapor pressure deficit (VPD) records at monthly temporal resolution were aggregated to provide yearly grid cell averages (tmean, VPD) and totals (ppt) across annual (all months), as well as the spring (March-May), summer (June-August), and autumn (September-November) seasons each year. For air temperature, winter (December-February) averages were included.

The AMSR surface fractional water (FW) records were aggregated to averages for the spring (when flooding is typically more rampant), summer and autumn periods.

The non-frozen season (NFS) length was derived from the SMMR/SSM/I/SSMIS Land Surface Freeze/Thaw State record using the “Combined” FT product (Kim et al., 2017, 2021), which uses information from morning and afternoon satellite passes. To identify the timing (i.e., day of year) and duration of annual surface frozen season for each grid cell, a “80% rule” moving window approach developed by Kim et al. (2012) for the northern hemisphere was applied. This approach identifies the primary date of annual surface thaw as the first day when 12 out of 15 consecutive days are classified as non-frozen (thawed) by the FT algorithm between January through June. The primary date of annual surface freeze is the first day when 12 out of 15 days are classified as frozen within the September through December period. Similarly, the 80% rule 15-day moving window approach was used to identify the first and last dates of annual snow cover within the ERA5 snow cover product. Annual surface non-frozen season length (NFS) was calculated for each grid cell (using each product’s native grid) as the total days between the identified thaw and freeze dates and identified snow-off and snow-on dates; NSF was also calculated for spring and autumn periods.

The annual and seasonal depths of soil thaw (ALT) for permafrost regions were estimated directly from the ESA CCI permafrost active layer thickness product. Soil moisture (SM) only included estimates over the annual non-winter period (spring through autumn).

For percent snow cover (SC), autumn, winter, and spring SC was calculated from the total pixel snow covered area as indicated by the ERA5 records for the given periods. SC was calculated per pixel, averaged by month, then averaged over the season. To assess annual SC within a domain, total seasonal coverages were summed.

For GIMMS3g normalized difference vegetation index (NDVI) and Vegetation Optical Depth Climate Archive (VODCA) vegetation optical depth (VOD) records, the grid cell data were aggregated to annual non-frozen season and to compute spring, summer and autumn averages for each year (excluding pixels where snow was present). Annual observations of per-pixel percent tree cover (TC) and non-tree cover (NTC) were obtained directly from the VCF5KYR v001 records.

Table 8. Description of remote sensing and model-based climate products used to identify regional changes in terrestrial properties across the Arctic-boreal permafrost zone. Key indicators of ecosystem condition were included to represent thermal state, landscape moisture, and vegetation. Observation frequency listed is native to the product

Product	Indicator Description	Spatial Resolution	Temporal Period	Observation Frequency
Thermal theme				
ERA5 ¹	Land Surface Air Temperature (tmean, °Celsius)	0.1 degree	1959 – 2020	Monthly Average
SMMR; SSM/I; SSMIS ²	Land Surface Non-frozen State (NFS, binary)	25 km	1979 – 2020	Daily
ESA CCI CRDP V.2 ³	Permafrost Active Layer Thickness (ALT, m)	926 m	1997 – 2019	Annual Maximum
Moisture theme				
ERA5 ¹	Precipitation (ppt, mm)	0.1 degree	1959 – 2020	Monthly Total
	Snow Cover (SC, percent)			Daily
	Vapor Pressure Deficit (VPD, kPa)			Monthly Average
	Near-surface Soil Moisture, depth 0-7 cm (SM, m ³ m ⁻³)			Monthly
AMSR-E; AMSR2 ⁴	Land Surface Water Fraction (FW, percent)	25 km	2003 – 2020	Daily
Vegetation theme				
GIMMS3g ⁵	NDVI (unitless)	0.08 degree	1982 – 2020	15-day
VODCA ⁶	Ku-band Vegetation Optical Depth (VOD, unitless)	0.25 degree	1988 – 2017	Daily
VCF5KYR v001 (AVHRR/MODIS) ⁷	Tree & Non-Tree Cover Fraction (TC and NTC, percent)	0.05 degree	1982 – 2016	Annual

Sources: ¹Hall et al. (2001, 2002) and Muñoz-Sabater et al. (2021).; ²Kim et al. (2017, 2021); ³Obu et al. (2021); ⁴Du et al. (2017), Jones and Kimball (2021); ⁵Pinzon and Tucker (2014); ⁶Moesinger et al. (2020); ⁷Hansen & Song (2018).

Trend analysis

To identify trends in these indicators, a non-parametric Mann-Kendall test was applied that detects monotonic upward or downward trends. The ZYP package in R (<https://cran.r-project.org/package=zyp>, version 0.10-1.1) was used, which provides z-scores and associated p-values. Where statistically significant trends were detected, the rate of change was measured by the Theil-Sen estimator of slope (median-based) for each time series. This approach was applied according to region-based averages over:

1. the full circumpolar Arctic domain, which encompasses northern North America (NA) and Eurasia (EA) zones;
2. individual NA and EA zones;
3. NA and EA zones separated according to tundra and boreal land cover. This approach has been used in past assessments of high latitude change. To detect finer grained patterns, this approach was applied to time series for individual pixels. This step revealed more localized changes that may not be reflected in Indicator averages over large regions.

These trends and their statistical significance are recorded in *_slope.tif and *_pvalue.tif files, respectively.

Change spot analysis

Unlike the Mann-Kendall approach, change spot analysis uses neighborhood-based statistics to detect significant clusters of change. Environmental Science Research Institute (ESRI; <https://www.esri.com/>) ArcGIS Pro version 2.9 software and the ESRI Emerging Hotspot Analysis (EHA; <https://pro.arcgis.com/en/pro-app/2.8/tool-reference/space-time-pattern-mining/emerginghotspots.htm>) algorithm was used for this purpose. To identify change “hotspots”, the EHA first applies a Getis-Ord G_i^* spatial statistic, which examines each pixel within the context of the neighboring pixels. A pixel surrounded by neighboring high or low values is more likely to be a hot or cold change spot, respectively. The Getis-Ord G_i^* statistic outputs z-scores and p-values and a hotspot bin classification. These hot and cold spot classifications are then evaluated with a Mann-Kendall trend test (Mann, 1945), which itself results in a z-score and p-value for each pixel within the temporal data. These z-scores and p-values are then used to determine the confidence of an emerging hot or cold spot. Output values range of values from -3 (99% confidence of a cold spot), -2 (95% confidence of a cold spot) -1 (90% confidence of a cold spot), 0 (no significant change), 1 (90% confidence of a hotspot), 2 (95% confidence of a hotspot), and 3 (99% confidence of a hotspot).

An EHA was first run on individual input Indicator variables according to annual and seasonal (winter, spring, summer, autumn) periods. The results are shown in the *_hotspot.tif files.

A multivariate hotspot ranking was applied based on Thermal, Wetness, and Vegetation change scenario themes (see Table 8) for the period of 1997 to 2020. These themes reflect landscape changes considered to be detrimental (e.g., a threat) to ecosystems and human populations. The Thermal multivariate ranking was based on increasing air temperature (tmean), increasing non-frozen season length (NFS), and increasing active layer thickness (ALT). The Moisture multivariate ranking measures decreasing precipitation (ppt), increasing vapor pressure deficit (VPD) and decreasing soil moisture (SM). The vegetation ranking indicates decreasing NDVI and decreasing vegetation optical density (VOD). The authors acknowledge that in some low-lying regions (e.g., the Alaska Yukon-Kuskokwim Delta) an increase in precipitation may be detrimental if it contributes to local flooding, but “decreasing precipitation” was considered as having an undesired impact on the region because of its overall influence on drought and ecosystem susceptibility to fire.

For the ranking scheme, a score of “1” to pixels was applied to pixels where only an individual Indicator showed a hotspot according to the selected change scenarios. A score of “2” was assigned to pixels when two Indicators showed hotspots of change. A score of “3” was assigned to pixels where three Indicators showed hotspots of change (Tables 3-6). The theme-based multivariate hotspot rankings are included in the 1997_2020_<month1>_<month2>_<theme>_combined_hotspot.tif files.

Ancillary files include shapefiles of ecoregion boundaries from Olson et al. (2001) that represent the Circumpolar Arctic, North America, Eurasia, Boreal region, Tundra region, North American Boreal, North American Tundra, Eurasia Boreal and Eurasia Tundra. Permafrost categories were from Brown et al. (2002). The land cover product *land_cover.tif* was developed from merged vegetation cover from the Circumpolar Arctic Vegetation Map (CAVM; Walker et al., 2005) and the ESA CCI-LC 2010 Epoch land cover (Kirches et al., 2014).

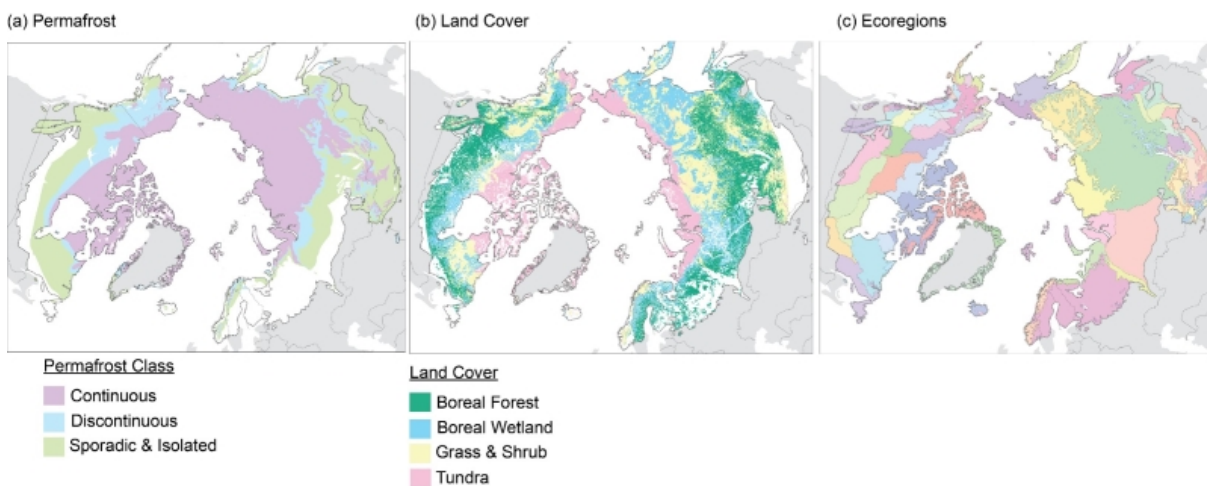


Figure 2. Maps showing the (a) spatial distribution of permafrost categories (continuous, discontinuous, sporadic/isolated; Brown et al., 2002), (b) land cover classes (Watts et al., 2024), and (c) delineations of the 58 ecoregions within the Arctic-boreal region (Olson et al., 2001).

See Watts et al. (2024) for details of the associated research.

6. Data Access

These data are available through the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

Trends of Thermal, Wetness, and Vegetative Change in the Circumpolar Arctic

Contact for Data Center Access Information:

- E-mail: uso@daac.ornl.gov
- Telephone: +1 (865) 241-3952

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