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Cool, CALM, collected: the Circumpolar Active Layer Monitoring program and network

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ABSTRACT

The Circumpolar Active Layer Monitoring (CALM) program is the primary global-change monitoring program concerned with the seasonally frozen active layer above permafrost. The active layer has been designated by the Global Climate Observing System and the Global Terrestrial Observing Network as an 'Essential Climate Variable'. CALM was launched in 1991 on a volunteer basis in cooperation with the International Tundra Experiment. CALM observatories in Russia and Alaska have been supported since 1998 by the U.S. National Science Foundation through five consecutive five-year funding cycles. In its current configuration, the CALM network includes observation sites throughout the circum-Arctic region and a substantial number of sites in Antarctica. Open access to data and data harmonization are hallmarks of the program. In addition to its ongoing emphasis on field observations of active-layer thickness, temperature, soil moisture, and thaw subsidence are currently being monitored at many sites. Increased emphasis is being placed on observing the dynamics of other landscape and ecosystem parameters, including vegetation, landscape patterns, and soils. Other developing features of the program include expanded education and outreach activities, close cooperation with other international programs, and provision of quality-controlled, standardized data products that meet the needs of the wider scientific community.

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Introduction

Until recent decades, most data sets concerned with the thickness, variability, and thermal regime of the active layer were obtained for the purposes of ecological, geomorphic, or engineering studies. Many past active layer monitoring efforts produced relatively short data records and provided little insight into long-term trends. Sampling designs and data-collection procedures were not standardized, making the accuracy of comparisons between sites and regions open to question. Information about the active layer in larger geographic and systems contexts was constrained by the absence of a suitable archive of consistent datasets.

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The CALM network represents the only coordinated and standardized program of observations designed to observe and detect long-term changes in seasonal thawing and freezing in high-latitude and mid-latitude, high-elevation soils. As part of this charge, the program is also concerned with differentiating between the impacts of long-term climate change and more localized geomorphic and anthropogenic effects.

A short history

CALM's early years

The Circumpolar Active Layer Monitoring (CALM) program was conceived in the early 1990s as a means to monitor the long-term response of the active layer and near-surface permafrost to climatic changes. The initial focus of the program, conducted under the auspices of the International Tundra Experiment (ITEX) (Molau & Molgaard, 1996), was concentrated on several efforts: (1) 'data rescue' activities focused on post-Soviet Russia (Barry et al., 1995); (2) creating an open-access data archive (FGDC, 2000–2004); (3) developing an international alliance of scientists contributing to a shared database (Barry, 1988); (4) critical field experiments (Nelson et al., 1999); and (5) creating a data-collection protocol (Fagan & Nelson, 2017). Many of these efforts had been effectively implemented by the mid-1990s (Brown et al., 2000) and thereby, the groundwork was laid for most of the components necessary for a comprehensive international monitoring network. The ongoing scientific concerns of the CALM program were described as observing and characterizing the temporal and spatial variability of active-layer thickness, active layer dynamics, near-surface permafrost-related processes, and the integrated response of these factors to changes and variations in climatic conditions. CALM also developed an outreach component very early in the program's development (Klene et al., 2002).

CALM I (1998–2004)

For CALM to be recognized as an international global-change monitoring program, the U.S. National Science Foundation's (NSF) Office of Polar Programs provided a five-year grant to the University of Cincinnati, under the direction of K.M. Hinkel, as part of the Arctic Transitions in the Land-Atmosphere System (ATLAS) initiative (Hinkel & Nelson, 2003; McGuire et al., 2003). The CALM network expanded during this period by developing new sites and incorporating existing sites in Russia, Alaska, Canada, China, Greenland, Kazakhstan, Mongolia, Norway (Svalbard), Sweden, Switzerland, and Antarctica, making the program both bipolar and circumpolar. The CALM I project funding provided field instrumentation, data loggers, and standardized protocols for active-layer measurements. The U.S. Natural Resources Conservation Service (NRCS) contributed instrumentation and personnel to field campaigns in both Alaska and Antarctica (Hinkel et al., 2000, 2001; Paetzold et al., 2000). A website was established and metadata and data were maintained at this web location, with periodic transfer to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. CALM data became an integral part of the CDs produced by NSIDC for the 7th and 8th International Conferences on Permafrost (Parsons et al., 2008; Parsons & Zhang, 2003).

Measurements both curated and conducted under CALM I represent a distillation of knowledge about the active layer and its behavior, as understood at the time the NSF proposal was written in 1997. The work focused on several interrelated hypotheses that guided field and analytic work from 1998 to 2003, as summarized by Nelson et al. (2008).

CALM II (2004–2010)

The achievements of CALM I created the possibility for a more comprehensive and integrated system of observations. The second five-year period of NSF support, administered through the University of Delaware and directed by F.E. Nelson, focused on several objectives: (1) maintenance and expansion of long-term, active layer observation programs in existing regional networks; (2) continued development of CALM's online database and provision of support for data management and a data archive; (3) development of standardized active-layer data sets to be used for validating hydrologic, ecosystem, permafrost, and climate models; and (4) integration of active-layer and thaw settlement observations across a range of temporal and geographic scales. A ground-based, non-invasive strategy for monitoring frost heave and thaw subsidence was developed using differential global positioning systems technology (Little et al., 2003) and implemented at several sites in northern Alaska (Shiklomanov et al., 2013; Streletsky et al., 2017). Subsidence measurements were expanded during the CALM II program using optical- and laser-leveling techniques (e.g., Mazhitova et al., 2008).

CALM's outreach component was developed further to include close involvement of local, predominantly indigenous populations in observational programs at remote Arctic sites (e.g.,Nyland et al., 2017). Outreach activities also expanded substantially in Russia, USA, and elsewhere with the advent of the International Permafrost Field Schools, conducted jointly by Moscow State University and George Washington University (Nyland, 2015; Nyland et al., 2013).

CALM III (2009–2015)

CALM received the next five-years of support, administered by George Washington University (GWU) under the direction of N.I. Shiklomanov, through NSF's 'Arctic Observing Networks' (AON) program. Several important developments accompanied the maturation of the program during CALM III, including (1) rigorous assessment of the efficiency of the observation network; (2) data integration; (3) refinement of the CALM website; (4) more than 50 peer-reviewed publications, including applications of three-dimensional ground-penetrating radar (Doolittle & Nelson, 2009) and global positioning systems (Shiklomanov et al., 2013) to problems involving the active layer. The circumpolar nature of the CALM network fostered increasingly extensive international collaboration between students and teachers involved in project activities. One unusual component of CALM's outreach activities was through close interactions with an inner-city New Orleans juvenile corrections facility and one of its teachers through the NSF-funded PolarTREC program (Davis, 2010; Dugat, 2010; PolarTREC, 2010). The number of CALM sites increased sharply during CALM III. An increasing number of measurements were stratified according to vegetation associations, landscape types, and soil characteristics (e.g., Hinkel & Nelson, 2003; Ukrainceva et al., 2012). Achievements under CALM III were summarized by Nelson and Shiklomanov (2010).

CALM IV (2014–2018)

The CALM IV program, sponsored by NSF and administered through GWU, continued the expansion of the observation network in terms of both site locations and types of measurements conducted. CALM developed formal partnerships with international organizations during this period, including the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS), the Circumarctic Environmental Observation Network (CEON), and the Climate and Cryosphere (CliC) programs. CALM is a component, with the Thermal State of Permafrost program, in the Global Terrestrial Network for Permafrost (GTN-P), developed in the 1990s by the International Permafrost Association under GCOS and GTOS https://gtnp.arcticportal.org/about-the-gtnp/sponsors.

Steady growth in the number of CALM sites occurred during this period. Applications of active-layer thickness (ALT) data in urban contexts occupied an increasingly important niche in the CALM program (Klene & Nelson, 2019; Nyland et al., 2017; Shiklomanov et al., 2017a, 2017b; Streletskiy et al., 2019).

CALM V (2019–2024)

The CALM V project, funded by the U.S. National Science Foundation (NSF) and administered through GWU and Northern Michigan University, is a component of the *Navigating the New Arctic* initiative, one of NSF's 10 foundation-wide long-term research and process ideas selected 'for future investment at the frontiers of science and engineering' (NSF, 2021). CALM V continues to emphasize field observations of active-layer thickness, temperature, soil moisture, and thaw subsidence monitoring. Increased emphasis is being placed on observing the dynamics of other landscape and ecosystem parameters, including vegetation, landscape patterns, and soils. As detailed in the next section, a program of site prioritization is under development and will be fully implemented by 2024.

Other features of CALM V include expanded education and outreach activities, expanded cooperation with other international programs, and provision of quality-controlled, standardized data products that meet the needs of the wider scientific community.

The CALM observation network, database, and applications

The CALM network grew from 125 sites at the close of the CALM I program to 274 registered sites at the beginning of CALM V. Data records from many of the volunteer international sites yielded only intermittent data, however, owing to difficulties with access and non-NSF funding. All of the volunteered records from such sites are, however, available through the CALM database.

The distribution of CALM sites is not uniform, a circumstance attributable to historical factors and logistical constraints. Sites were established in regions of economic activity and/or in areas of long-term climatic, permafrost, and ecosystem research. This logistically driven approach to site selection was adopted to ensure regularity and periodicity of measurements. With the launch of CALM V, a new site classification is being developed that will prioritize collection efforts, as advocated by Anisimov et al. (2007). This site classification will be based on data record length and continuity, geographic distribution,

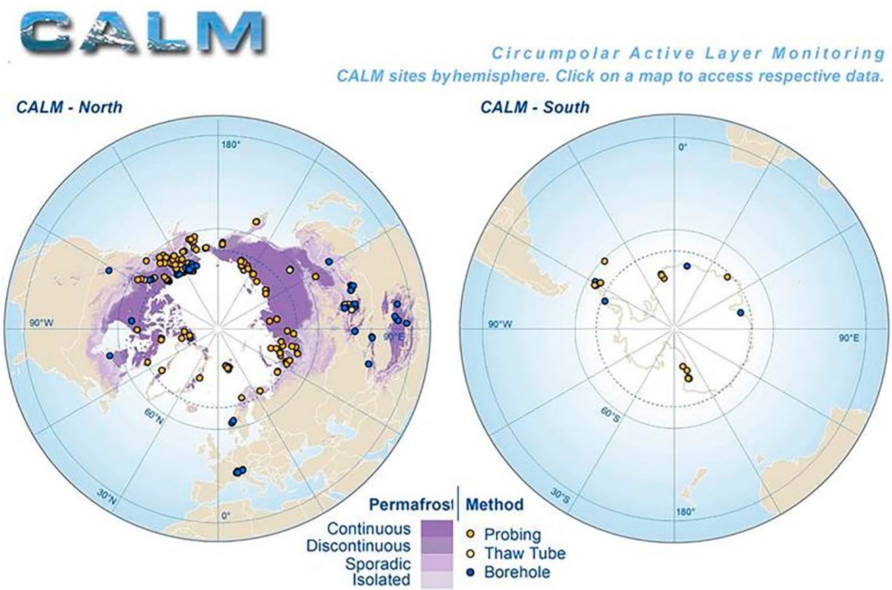

Figure 1. Permafrost distribution and locations of active CALM sites in Northern and Southern Hemispheres. Sites are grouped according to active-layer monitoring methods. Further information is available from the CALM website. https://www2.gwu.edu/~calm/.

intra- and interannual consistency in observation timing, and logistical constraints. There are currently 141 'active' sites, defined as having reported data collected since 2017. Figure 1 shows the distribution of these sites. Under CALM V this subnetwork of 25–30 high-priority sites will be distributed at relatively uniform intervals, throughout the Arctic and Subarctic, and representative of major landscape types. These sites will receive priority support for expanded, standardized instrumentation.

Analysis, archiving, and distribution of CALM's long-term observations are integral components of the program. Field data are provided by participants on an annual basis. These data are incorporated into the CALM database and made available through the CALM website https://www2.gwu.edu/~calm/ and the U.S. National Science Foundation's Arctic Data Center www.arcticdata.io.

CALM-S

An important development during CALM III was the creation of a formal program of CALM observations in the Southern Hemisphere, including on the Antarctic continent, in the maritime sub-Antarctic islands, and eventually in the Andean Mountains. This group of CALM sites is known collectively as the CALM-South (CALM-S) network. CALM-S grew out of a 2004 conference focused on Antarctic permafrost and soils (Boc- kheim, 2005), and was developed to investigate conditions across environmental gradients from the Andes to the sub-Antarctic islands and through the Antarctic Peninsula and Transantarctic Mountains to the McMurdo Dry Valleys. The program has yielded important results, described in numerous publications (e.g. Bockheim & Hall, 2002; Guglielmin, 2006; Hrbáček et al., 2021; Ramos et al., 2007; Vieira et al., 2010).

Model validation

Active-layer observations and auxiliary information from the CALM network provide a circumpolar database, which has been used extensively to validate process-based geocryological and hydrological models. Because CALM investigators follow a standardized, well-documented protocol, data from the program are useful for validating modeling efforts, at a variety of geographic scales. CALM was identified as a model program with respect to data harmonization in the U.S. National Research Council report *Toward an Inte- grated Arctic Observing Network* (National Research Council, 2006). The use of CALM data for model validation was discussed in detail in Shiklomanov et al. (2008). Results from intercomparison of modeled active layer fields were described by Shiklomanov et al. (2007).

Integration

Data integration, spatial interpolation, and creation of regional representations of ALT are critical concerns in the CALM program. Nelson et al. (1997) and Shiklomanov and Nelson (2002) created maps of ALT for a 27,000 km^2 area of north-central Alaska, and conducted validation studies by helicopter survey (Muller et al., 1998; Shiklomanov & Nelson, 2002). A spatial time series extending over more than 25 years now exists for this region as described by Nyland et al. (2021) in this issue. Another regional map based partially on CALM data is the detailed digital landscape and active-layer map created at the Earth Cryosphere Institute of the Russian Academy of Sciences (Ukrainceva et al., 2012). This regional compilation embraces a hierarchy of data layers, including landscape units, organic layer thickness, lithology, and landscape-specific characteristic values of active-layer thickness in the northern part of West Siberia. Other regional efforts are in progress.

Contributions to theory

The CALM program has demonstrated repeatedly that a well-conceived monitoring program can contribute substantially to the development of scientific hypotheses and theory. Prior to the mid-1990s, most research treating permafrost-climate interactions was based on a two-component conceptual model involving (a) a seasonally frozen active layer and (b) underlying perennial frozen materials. Analysis of data obtained from CALM sites indicated, however, that this concept is not adequate to explain the behavior of the active-layer/permafrost system, particularly in ice-rich terrain. To an observer measuring ALT using traditional methods, such as mechanical probing, thaw penetration into the ice-rich layer may not be apparent, owing to thaw consolidation and net subsidence of the surface over long time periods.

The stability of ALT in many Arctic landscapes, as suggested by many CALM records, indicates the existence of self-regulating mechanisms that contribute a robustness to the upper permafrost with respect to external climatic forcing. In many regions, an ice-rich transient layer exists below the base of the active-layer. Because of latent-heat effects, the transient layer can resist thaw and tend to promote long-term stability in the position of the base of the active layer. However, during unusually warm summers, thaw may penetrate the ice-rich transient layer. Conversely, following colder summers ice may be added to the upper permafrost, resulting in a decrease of ALT. Although the magnitude, frequency, and variability of this apparent Markovian-like behavior are not widely documented, they appear to be responsible for abrupt, long-lasting changes in ALT at CALM sites near Utqiagvik, Alaska (Nelson et al., 1998; Nyland et al., 2020).

Shur et al. (2005) discussed the characteristics and behavior of a ternary permafrost system incorporating the transient layer. The primary characteristics of such a system are the different periodicities at which the constituent layers cycle through 0°C and the relative abundance, morphology, and distribution of ice contained in each. Although the ice-rich character of the transient layer acts to retard its rate of degradation, progressive thaw under monotonic climate warming would lead to its destruction, accompanied by thaw consolidation and differential subsidence at the surface. Elimination of the most ice-rich parts of the transient layer may be accompanied by an abrupt and long-lasting increase in the thickness of the active layer. Thaw penetration into spatially heterogeneous ground ice in the underlying permafrost triggers differential thaw settlement at the surface.

Simultaneous monitoring of active-layer thickness and thaw subsidence has been undertaken at several ice-rich CALM sites in Alaska and Russia. To account for ground subsidence in the active layer record at several CALM sites in northern Alaska, annual changes in the position of the ground surface, relative to the level at the beginning of the measurements in the year 2000, were added to the active layer measurements produced by mechanical probing (Shiklomanov et al., 2013; Streletsky et al., 2017). Results from sampling locations at several sites in northern Alaska indicate a monotonic increase in thaw penetration over the period of measurement (Streletskiy et al., 2008). Similar results have been obtained elsewhere on Alaska's North Slope and in Russia. Widespread stratigraphic evidence for fluctuations in the position of the transient layer have been found in northern Alaska (Bockheim & Hinkel, 2005). Taken together, these results indicate that the CALM program should continue to install instrumentation for monitoring of thaw subsidence at sites containing abundant ground ice at shallow depth.

The CALM workshops

An NSF-funded international CALM workshop was held in late 2002 at the University of Delaware. The workshop provided an opportunity for CALM participating scientists to present data and site histories, review methodologies, discuss progress and problems in the network, implement unified data-analytic procedures, and plan future activities. Discussions and collaborations arising from the workshop resulted in a series of regional papers and poster abstracts addressing the spatial and temporal variation of active-layer thickness at a large number of Eurasian and North American and other sites (Nelson, 2004a, 2004b).

A second workshop was held in Fairbanks, Alaska during 2008, in connection with the Ninth International Conference on Permafrost. The workshop employed activities similar to those of the first workshop six years earlier. Particular attention was given to developing the network in boreal and Antarctic regions, and for developing the capacity to monitor frost heave and thaw subsidence. Results from the workshop were used to develop a new proposal to NSF for the CALM III program.

The third CALM Workshop was held in Potsdam, Germany in 2016, in association with the 11th International Conference on Permafrost. The workshop consisted of a series of scientific presentations and discussions about the future course of the CALM program. Plans were also developed for the publication of this special issue of *Polar Geography* to highlight recent progress at existing sites, as well as descriptions and analysis of data from sites recently added to the network.

Into the future

Reflecting its open, community-based structure, CALM holds meetings and round-table discussions in connection with major scientific conferences. Educational and outreach activities are also an integral part of the CALM strategy. The program will continue to provide opportunities for field experience and educational participation at levels ranging from elementary school through postdoctoral. The circumpolar nature of the CALM network will foster extensive international collaboration between students involved in project activities. An outreach component includes extensive involvement of local and indigenous residents in remote areas. CALM will continue to incorporate data into its web-accessible database from existing and new sites. The program will continue to foster existing collaborative relationships and to develop new ones with international observational networks and research programs.

The COVID-19 pandemic hindered or prevented data collection at some CALM sites during 2020, but the program's cooperative structure facilitated data acquisition in many localities by local and indigenous partners. CALM has become increasingly involved in such partnerships (e.g. Herman-Mercer, 2017; Nyland et al., 2017; Schuster et al., 2011).

The year 2021 marks the 30th anniversary of the CALM program. This special issue contains a representative sample of long-term CALM observations from several permafrost regions: Alaska (Nyland et al., 2021), Russia (Abramov et al., 2021; Kaverin et al., 2021), and Antarctica (Hrbáček et al., 2021). They illustrate the intensive fieldwork, innovative procedures, open data access, and cooperative international structure of the CALM program. These traits will ensure the program's continuing relevance and value to cryospheric science.

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Data availability statement

CALM data are available from the CALM website (https://www2.gwu.edu/~calm/data/data-links.htm) and the U.S. National Science Foundation's Arctic Data Center (www.arcticdata.io).

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