Permafrost, Phillips, Springman & Arenson (eds)
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Permafrost distribution in the Appalachian Highlands, northeastern USA

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ABSTRACT: Rugged terrain and lack of soil temperature and borehole data necessitate use of a climate-based assessment of permafrost distribution in the Appalachian Highlands of the eastern United States. The presence of permafrost has been confirmed through direct observation only on Mt. Washington in New Hampshire. A five-year climate record, obtained from fourteen summit and five other high-elevation sites along a 1500 km transect from Maine to North Carolina, provides evidence to support the contention that permafrost occurs at high elevations on several mountains in New York and New England. Climate data from summit locations were used with well-documented lapse rates, specific to the Appalachian Highlands, to estimate the elevation of the 0°C mean annual air temperature isotherm throughout the region. Holding elevation constant, mean annual temperature decreases 0.54°C per 100 km northeastward along the transect. The altitudinal trend of this isotherm is parallel with, but much higher than, the mean elevation of relict periglacial blockfields throughout the transect.

1 INTRODUCTION

The distribution of permafrost in high-latitude regions has received much attention in recent climate-change literature. Paleoclimatological and historical evidence indicate that mountainous areas are highly sensitive to climate change (IPCC, 1996, Beniston et al., 1997), and mountain permafrost has received considerable attention in recent years (e.g., Etzelmüller et al., 2001; Harris et al. 2001). Nonetheless, mountain permafrost in the contiguous United States, particularly in the eastern part of the country, has been largely overlooked (Péwé, 1983) with only one major study having been undertaken in northeastern USA (Schmidlin, 1988).

The presence of permafrost has been confirmed on Mt. Washington through direct observation (Bent, 1942, Howe, 1971, Moyer, 1978), but little else is known about its distribution in the region. Because the climatic conditions necessary for the occurrence of permafrost are marginal, its distribution in the study area is highly discontinuous. Numerous periglacial landforms have been reported in the Appalachian Highlands (Clark and Ciolkosz, 1988, Clark and Schmidlin, 1992), but most are considered relict from past cold intervals and yield little information about the distribution of contemporary permafrost.

Accurate maps of the distribution of permafrost are important for studies of climate change and engineering applications (IPCC, 1996). However, the rugged and highly variable Appalachian terrain inhibits generalization of soil temperature data, further complicating mapping efforts. These obstacles necessitate use of climate-based assessments of permafrost distribution. Even this approach is made difficult by the fact that existing weather stations are concentrated in valley bottoms (Leffler, 1981, Schmidlin, 1982) and few data are available from summit locations. Despite these difficulties, Schmidlin (1988) made preliminary estimates of permafrost distribution in the Appalachians, based on temperature data from Mt. Washington and lapse rate equations specific to the region (Leffler, 1981). Little progress has been made since, owing to the lack of air temperature data from summit and other high-elevation locales.

2 INSTRUMENTATION

To address the problems outlined above, a special network consisting of nineteen high-elevation climate stations was established along a 1500 km transect extending from Maine to North Carolina (Figure 1).

Figure 1. NE-SW transect and location of the fourteen mountains in the high-elevation network.

Stations in the network currently consist of a dual-channel Onset Hobo Pro© miniature data logger reading air and ground-surface temperature at hourly intervals, and three single-channel Onset StowAway© loggers reading temperature at depths of 10, 25 and 50 cm in the soil at two hour intervals. Air temperature sensors operate in six-gill radiation shields mounted on tethered masts at 1.8 m above the ground surface.

Fourteen Appalachian Mountains were selected for instrumentation based on their summit elevation, overall distribution, and accessibility. Each mountain was instrumented with a climate station on or as close as possible to the summit. Five additional sites were situated on north-facing slopes midway between the base and summit of mountains supporting summit instrumentation. The sites range in elevation from 326 to 1989 m above sea level. Data collection began in August 1996 and continues to date. Detailed descriptions of the sites, instrumentation, and data records are provided in Walegur (2001).

The distribution of sites in the high-elevation network is an extremely important consideration owing to the scarcity of air temperature data from summit locations, where permafrost is most likely to exist. The data from summit sites have also provided information about lapse rates and latitudinal temperature trends unique to the Appalachians, previously addressable only through generalized calculations (Leffler, 1981).

3 CLIMATOLOGY

3.1 *Lapse rates*

Adiabatic cooling refers to the general process by which air temperature decreases with increasing height in the troposphere. Environmental lapse rates of −6 to −7°C/km are frequently used in applied studies but, strictly speaking, are only applicable to the free air. Given the reality of heterogeneous ground cover, cold-air drainage and radiational cooling within the Appalachians, these relations can be regarded only as crude approximations (Walegur, 2001).

Leffler (1981) addressed this problem by using long-term (>30 yr) temperature records from Mt. Washington and Pinkham Notch (a low elevation crest near Mt. Washington) to estimate mean monthly lapse rates in the Appalachians (Table 1). These estimates are similar to lapse rates previously cited for the Appalachians by Landsburg (1943) and Fobes (1970). For comparison, lapse rates were calculated using data collected from the five mountains with climate stations at two elevations. Although these records are not of the same duration or from the same time period as those used by Leffler (1981), results are similar (Table 1).

3.2 *Latitudinal temperature trends*

The Appalachian Mountain Range is a narrow, linear physiographic feature that lends itself well to studies of climatic elements at various elevations along a latitudinal transect. Holding elevation constant, Leffler (1981) estimated a change in mean annual temperature of 1.08°C for each degree of latitude. Hopkins (1960) and Lee (1969) cited similar values (1.1°C/°lat) of temperature change in less extensive subareas of the Appalachians. Walegur (2001), using the more extensive high-elevation database, obtained a value of 0.94°C/°lat over the 1500 km transect.

Table 1. Monthly and annual lapse rates (°C/km) for the Appalachians as calculated by Leffler (1981) and Walegur (2001). The second column gives lapse rates calculated between Mt. Washington and Pinkham Notch from 30-year records. The third column depicts the mean lapse rates calculated from the high-elevation climate stations over a five-year period.

Setting	Leffler (1981)	Walegur (2001)
January	4.4	5.0
February	5.2	4.9
March	6.2	4.7
April	6.5	6.4
May	6.6	4.8
June	6.2	4.7
July	6.3	5.0
August	6.2	5.5
September	5.7	4.7
October	5.9	5.5
November	5.4	5.7
December	4.6	4.6
Annual	5.8	5.1

Table 2. Monthly and annual temperature trends. The second column represents temperature change (°C per °latitude), calculated by Leffler (1981). The third column represents temperature change in °C per 100 km along the line of relative latitude depicted in Figure 1.

Setting	Leffler (1981)	Relative Trend
January	1.4	0.90
February	1.5	0.81
March	1.3	0.56
April	1.3	0.60
May	1.1	0.38
June	0.8	0.27
July	0.8	0.29
August	0.8	0.31
September	0.9	0.40
October	0.9	0.61
November	1.0	0.63
December	1.3	0.73
Annual	1.08	0.54

Because the Appalachians do not have a perfect north-south alignment, it is necessary to examine the spatial trend of temperature parallel with the long axis of the mountain range. Carter and Ciolkosz (1980) used this approach to estimate soil temperature trends in the central Appalachians. A transect evenly bisecting the 20 high-elevation data collection points was constructed using reduced major axis procedures and UTM coordinates (Figure 1). The positions of the data collection points were then projected onto the transect line using the cosine function. The effects of elevation were removed by normalizing all temperature data to sea level using Leffler's long-term (1981) lapse rates (Table 1). Table 2 shows monthly temperature trends with latitude (Leffler 1981) and along the line of "relative latitude" depicted in Figure 1.

3.3 *Applications*

Approximations of permafrost distribution in regions lacking soil temperature data frequently rely on mean annual air temperature (MAAT). Péwé (1983) suggested that a MAAT of 0 to −1°C is necessary for permafrost to persist. Brown (1969) noted the presence of permafrost in eastern Canada at locations where the MAAT is just below 0°C. The latter case was attributed to the mild summers typical of the region.

In his preliminary assessment of permafrost in the Appalachians, Schmidlin (1988) used Leffler's (1981) equations to identify the elevation of the 0, −1, and −2°C isotherms throughout the northern Appalachians. His work indicates that the lower limit of permafrost decreased by approximately 185 m per degree increase in latitude. Schmidlin's (1988) work was based solely on data from Mt. Washington and Leffler's equations, so it is desirable to estimate the elevation of the 0°C isotherm along the line of relative latitude in Figure 1 using data from the high elevation climate stations. The elevation of the 0°C isotherm was calculated for each site using Leffler's (1981) long-term lapse rates and the mean annual temperature and elevation of each site. Figure 2 depicts the estimated elevation of the 0°C isotherm.

Walegur et al. (2001) presented data supporting the importance of this latitudinal temperature trend for paleogeographic studies within the Appalachians. The median elevation of relict periglacial blockfields decreases consistently with increasing latitude over the same transect. This trend is lower in elevation and parallel to the trend of the 0°C isotherm presented in Figure 2, indicating a strong climatic control over the elevation of blockfields, which are thought to have formed during Quaternary glacial advances.

3.4 *DEM-aided interpolation*

Synthesis of topographic information with analytic techniques developed in climatology forms the basis of a subfield known as *topoclimatology.* This topic has been recognized as a distinct branch of climatology since the early 1950s (Thornthwaite, 1953). The ultimate goal of topoclimatology is quantitative analysis of heat and moisture exchange between the atmosphere

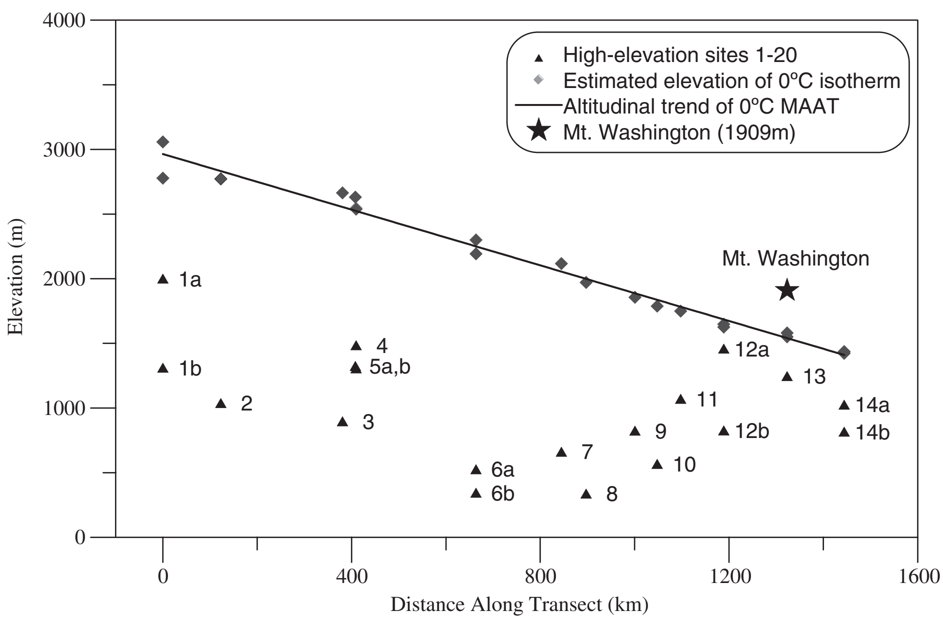

Figure 2. Estimated elevation of the 0°C MAAT isotherm along the transect in Figure 1. The Coefficient of Determination is 0.98 for the line of best fit. Distances are given in km from the southernmost site (Mt. Gibbes, NC). Diamonds represent the estimated elevation of 0°C MAAT using temperature data from each site and Leffler's lapse rate equations. MAAT of Mt. Washington is −2°C.

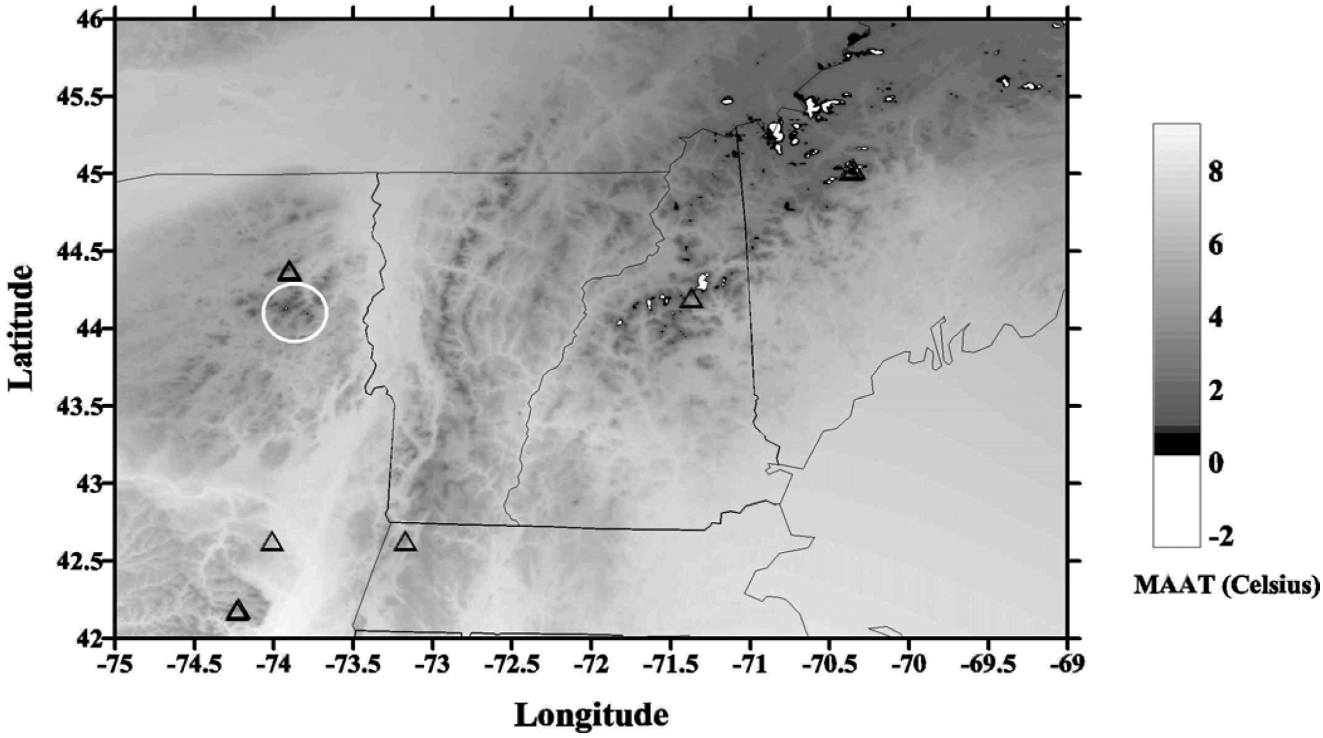

Figure 3. Interpolated map of mean annual air temperatures (1997–2001) for the northern Appalachian Mountains. White represents areas with MAAT 0°C or below. High-elevation climate stations are depicted as triangles. The white circle directs attention to an inconspicuous area of potential permafrost in the High Peaks Region, NY. The Atlantic Coastal Plain and northwest portions of the map are shown for cartographic completeness only. The temperature field is valid only for the Appalachian Mountain Range.

and surfaces of varying elevation, orientation, gradient, and surface cover. This task is complicated in studies of mountainous regions, where the effects of slope angle, aspect, and elevation can cause large thermal and moisture gradients over relatively short distances.

Willmott and Matsuura (1995) outlined a method that allows the effects of elevation to be removed from interpolated temperature fields. This strategy, known as "DEM-aided interpolation," has been employed in cold regions by Nelson et al., (1997), and Tveito and Forland, (1999). The technique involves normalizing air temperature records from point locations to sea level using lapse rates and the elevation of each data point. Various interpolation procedures can then be applied to create sea-level air temperature fields for the area of interest. The sea-level temperature fields are then readjusted ("cooled off") by reducing the interpolated temperatures based on elevation and a standard lapse rate.

In an earlier study of Appalachian temperature fields, Walegur and Nelson (2000) demonstrated that DEM-aided interpolation, used in conjunction with Leffler's long-term mean monthly lapse rates, provides more accurate temperature estimates than those relying on an arbitrary lapse rate within the confines of the study area. DEM-aided interpolation methods therefore have great potential for mapping the extent of Appalachian permafrost.

To map the distribution of the 0°C isotherm, air temperature data from 63 first-order and cooperative weather stations (NCDC, 2001) were used in conjunction with data from the nineteen high-elevation climate stations and Leffler's (1981) 30-year lapse rates to generate mean annual temperature fields for the Appalachians using a DEM-aided interpolation routine (Figure 3).

4 RESULTS

The general trend of decreasing temperature with increasing latitude is clearly visible in Figure 3. The effects of terrain are also apparent. The Catskill, Adirondack, Green, and White Mountain ranges of the northeastern U.S. have colder temperatures than the Hudson River Valley and Lake Champlain basin. The summit of Mt. Washington is also identifiable by its subzero mean annual air temperature.

Although permafrost is ultimately a climatic phenomenon, the thermal properties of the substrate and the effects of snow cover are critical factors influencing the southern and lower elevational limits of permafrost (Schmidlin, 1988, Smith and Riseborough, 2002). Hence, even physically based maps of mean air temperature have limitations. To map permafrost

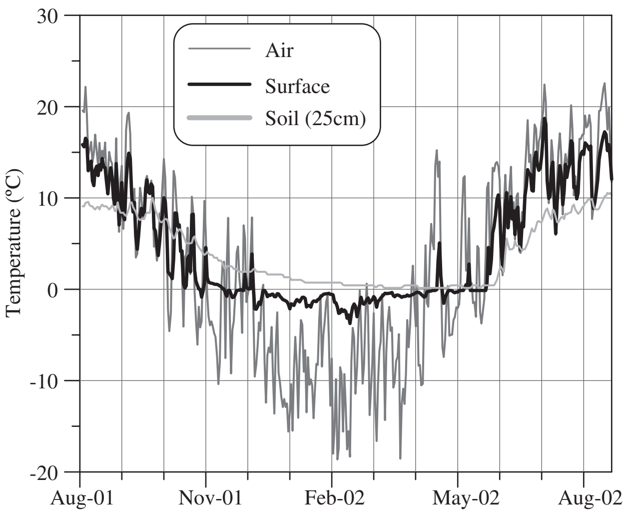

Figure 4. Mean daily air and soil temperatures at Mt. Jackson, NH (1235 m).

in the Appalachians accurately, further attention must be given to the effects of soil type, vegetation, and snow cover.

With the exception of several bald peaks above climatic timberline, the Appalachian Mountains are largely vegetated. "Balds" are likely locations for permafrost because strong winds remove snow from these areas during winter, eliminating the effects of the "nival offset" (Smith and Riseborough, 2002).

New Hampshire's Presidential Range, most famous for Mt. Washington, also contains Site 13 on the summit of Mt. Jackson. At 1235 m, Site 13 occupies a transitional climate zone between the alpine tundra above and the spruce forest below. This site is surrounded by krummholz (<2 m), which effectively accumulates snow. Figure 4 shows mean daily air and soil temperature (surface and 25 cm depth) from Site 13. The temperature curves clearly demonstrate the important influence of snow cover on soil temperature at such locations. Despite the fact that air temperature was well below −15°C for extended periods surface temperatures never dropped below −3.75°C, while soil temperature at a depth of 25 cm achieved a minimum of only 0.15°C. Clearly, permafrost at this location is restricted to sites that carry a limited snow load in winter.

5 CONCLUSIONS

Permafrost is known to exist on Mt. Washington and is likely to be present at several other high-elevation locations within the northern Appalachians of the eastern United States. Based on Figure 3 the best candidate localities for permafrost are the High Peaks Region of New York, the Presidential Range of New Hampshire, and several areas in northern Maine. A relatively high concentration of potential sites occurs along the border between Maine and Canada. Specific mountains include: Mt. Marcy and Whiteface Mt., NY; Mt. Washington, NH; and several peaks in Maine including, Sugarloaf Mountain, Snow Mountain, Crocker Mountain, and Mt. Katahdin.

Maps such as the one presented in this study provide valuable information about the broad-scale distribution of permafrost in areas where it is highly discontinuous, and indicate where future field-based studies should be concentrated. The integrated effects of soil type, surface cover, site orientation, and snow are poorly documented within the study area, and more soil temperature data are needed to obtain information about the detailed, local-scale distribution of permafrost in the northern Appalachians. Only with such information will confirmation of climate-based maps of permafrost be possible.

ACKNOWLEDGEMENTS

A. Lapenis and F. Henderson (SUNY Albany) commented on an earlier version of the manuscript. We thank A. Klene for assistance with figures and editing, N. Shiklomanov for technical advice, and T. Schmidlin for encouragement throughout the project. The College of Arts and Sciences, University of Delaware, provided partial financial support for establishing and maintaining the Appalachian high-elevation climate network.

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