Climatic Relationships of Permafrost Zones in Areas of Low Winter Snow-Cover

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ABSTRACT. In areas with under 50 cm snow cover in winter, the permafrost zones show diagnostic long term freezing indices and thawing indices. The warmer boundary of the zone of continuous permafrost traverses the mean annual air temperature (MAAT). The boundary between discontinuous and sporadic permafrost lies just on the cold side of 0°C MAAT. The sporadic permafrost zone includes the zone of ice caves and the regions with patches of ice beneath ponds and peatbogs, extending to 5°C MAAT at a thawing index of 4000 degree days per year. The relationship is applicable to Norway, Iceland, Spitsbergen, Canada and the People’s Republic of Mongolia.

There are some marked variations in lapse rate from one environment to another, the most marked of which occurs above tree line where the lapse rate increases markedly in winter, though not in summer. This produces a change in MAAT of 2.5°C on Plateau Mountain. The changes also occur at non-permafrost areas and it appears likely that they are due to spatial and seasonal changes in albedo. Whatever the cause, the variations in lapse rate indicate that calculations of past world climatic change based on data from one area may be misleading.

INTRODUCTION

The most extensive areas of permafrost are found in the large northern countries of the world, viz., Canada, China, and the U.S.S.R. As a result of the vast areas to be mapped, there is a severe problem in delimiting its distribution in many areas, e.g. the Rocky Mountains of North America. Given adequate technological help (e.g. Harris and Brown, 1978), the permafrost distribution can be determined in localized areas, but producing a detailed map of its distribution along the Rocky Mountains remains a formidable task.

Clearly, it is necessary to develop a reconnaissance tool capable of predicting the possible distribution of permafrost in large areas of mountainous terrain, so that these predictions can be checked on the ground. Since the usual diagnostic features of lowland permafrost regions (pingos, palsas, patterned ground, etc.) are either absent or unobtrusive in mountainous terrain, air photo-interpretation is not a complete answer. Climate is the major determinant of permafrost (Ferrians and Hobson, 1973) and although other factors are involved (see for example Brown, 1973), it still holds the best possibilities for this type of prediction at a reconnaissance scale. This paper discusses a new method of climatic prediction for specific conditions which are fairly widespread in permafrost regions. It then examines the spatial variation of some climatic data from semi-desert to permafrost regions in parts of western North America.

PAST WORK

Many attempts have been made to match climatic parameters with the distribution of the features associated with permafrost. Black (1951) realized the difficulty of the problem when he used a 0 to -3°C mean annual air temperature (MAAT) as a characteristic of permafrost regions. Subsequently, Nichols (1956) noted a MAAT of -2.6°C for a permafrost location in the discontinuous zone. Kaiser (1960) claimed that the limit of continuous permafrost in Siberia was bounded by the -2°C mean annual isotherm, although others have suggested different values.

In Canada, Pihlaihen (1962) placed the southern boundary of permafrost at between -1.1 and -3.9°C MAAT. However, Reduzobov (1954), Péwé (1956), Brown (1967a), Brown and Péwé (1973) and others have concluded that the boundary approximated the -1°C MAAT isotherm. In an earlier discourse, Brown (1960) concluded that there was no close correlation between permafrost and air temperature in Canada and the U.S.S.R. Subsequent studies of the boundaries have tended to support this conclusion, but it has also become obvious that there are some very important factors that interfere with a simple climatic relationship (Brown, 1973). These include

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depth of snow cover, vegetation, hydrology, lithology and
topography.

Sanger (1966) and Thompson (1966) have discussed the
importance of degree-days in engineering studies, while
others (Brown, 1960; Washburn, 1973) have published
maps of freezing and thawing indices based on mean daily
temperatures below and above the freezing point respec-
tively. Unfortunately these have not previously been
correlated with observations of the occurrence of perma-
frost. It is the possibility of this relationship that will be
studied below.

LIMITING CONDITIONS

If the MAAT is plotted against elevation for the Class A
weather stations between latitudes 50° and 52°N in souther-
n Alberta, the results show considerable scatter (Fig. 1).

If the mean annual air temperature is plotted against the
ground temperature at the surface of the zone of zero
annual amplitude, again the predictive ability is poor, even
though the correlation is obvious (Fig. 2). However, if we
examine the geotherms for a given site (Fig. 3), there are
clearly two basic waves of energy flow into and out of the
soil. Although chinooks are common in Calgary, their
effect is dwarfed by the seasonal effects of heating in
summer and cooling in winter. Thus, the concept of using
freezing and thawing indices appears to be basically
sound.

FIG. 1. Mean annual air temperature versus altitude for all the Class A
weather stations between 50° and 52° N in Alberta. The boundaries of the
Parkland vegetation zone are indicated by the dashed lines around 1210
and 1350 m altitude.

FIG. 2. Mean annual air temperature versus ground temperature at the
top of the zone of zero annual amplitude (after Brown, 1967a; Smith,
1975; Harris and Brown, 1978).

It is well known that a thick snow cover acts as an
insulating layer, preventing the cold from penetrating the
ground (Krislinley, 1963; Brown, 1973; Harris and Brown,
1978; Nicholson, 1976, 1978a). The critical question is
what thickness of snow inhibits winter cold penetration
into the upper layers of the soil so that only seasonal frost
will be present. We have data from a number of sites at the
margin of permafrost at Plateau Mountain showing
varying thicknesses of snow cover in January, February,
and March (Fig. 4). The critical thickness appears to be 50
cm in southern Alberta at a freezing index of about 2250
degree-days/year and a thawing index of about 750 degree-
days/year. Thus the freezing and thawing indices can only
be expected to yield consistent results in predicting the
presence or absence of permafrost where the average
winter snow cover does not exceed 50 cm. This is only
important in the higher altitudinal zones along the Pacific
Coast and in Québec; it does, however, explain why perma-
frost is sporadic over such a wide area of Québec
(Brown, 1975).

The experience of Brown (1973) with lithological, hy-
drological, topographic, and biological factors must also
be borne in mind, but is not too serious as long as peaty
deposits are treated separately from mineral soils. Wet
sites also differ appreciably from dry sites. However, the
permafrost maps accommodate the variability by using
continuous, discontinuous and sporadic classes on maps
(see the discussion in Harris, 1979).

PERMAFROST ZONES AND FREEZE-THAW INDICES

The permafrost zones in parts of Canada were pro-
visionally mapped by Brown (1967a) and have been re-
examined in Québec by Brown (1975) and Nicholson
(1978b), and in the prairies by Zoltai (1971). A start on the
detailed distribution in the Rockies has been made by

Figure 5 shows the results of plotting freezing indices against thawing indices for Canadian stations where there is less than 50 cm of snow cover between December and March. The type of permafrost zone for each site is also indicated and it will be seen that the data plot in discrete zones. Included in the data points are information from Iceland (Priesnitz and Schunke, 1978), Spitzbergen (Jahn, 1976; Norske Meteorologiske Institutt, 1963-74), Norway (Ahman, 1977; Norske Meteorologiske Institutt, 1963-74), and the Mongolian People’s Republic (Gavrilova, 1978; Gravis et al., 1978). The data from different countries and observers agree very well.

The continuous permafrost zone in Figure 5 is bounded by a curve which transgresses the isotherms of mean annual temperature, which explains why the literature from different areas is confusing. The zone of discontinuous permafrost extends almost to the 0°C isotherm. Beyond it lies a zone of sporadic permafrost in which some sites show either ice caves or patches of ice beneath lakes or in peatlands. The zones of ice caves and ice patches in wet places appear to be coincident. Clearly more attention will need to be paid to this zone in future. The zone of ice caves in Eurasia has yet to be mapped, but is fairly widespread, e.g. ice caves occur in the Crimea.

NEAR-SURFACE LAPSE RATES

If freeze-thaw indices are the key to the climatology of the permafrost zones, they can also be used to check the validity of the concept that near-surface temperatures change at a constant rate with climatic change. Such an assumption is needed in predicting world-wide climatic changes using evidence of climatic changes at a single location, and is widely used in palaeoclimatic interpretations. It was also the basis of the earlier work of Brown (1967a).
The relationship between occurrence of permafrost zone and the plot of freezing index versus thawing index for stations in Canada, Norway, Spitzbergen, Iceland and the Mongolian People's Republic. The indices are based on a minimum of two years' data and usually 10-25 years.

If the lapse rate is constant, then the plot of freezing and thawing indices along a line of latitude should plot as a straight line on the freezing index-thawing index plot. However, when the 1974-75 indices for the weather stations lying along the 50°N parallel from Medicine Hat (MH) to Plateau Mountain (PM) in Southern Alberta are plotted as in Figure 5, they plot in a dog-legged form with a marked change occurring at about the boundary of the sporadic and discontinuous permafrost zones (Fig. 6). Similarly, the 1974-75 data for the stations lying along a line from Medicine Hat via Edmonton, Great Slave Lake to Inuvik (Fig. 7) were plotted on the same diagram. Once again a series of straight lines appeared. Clearly, lapse rates vary abruptly from place to place at certain points on the landscape in a manner not previously considered.

Figure 8 shows the results of plotting the freezing indices and thawing indices against altitude for the data between Medicine Hat and Plateau Mountain. The thawing index shows a moderate scatter but the data can be approximated by a straight line. However, the freezing index shows an abrupt change above the upper tree line. Here the lapse rate increases considerably, but there are insufficient data to establish the exact slope of the new rate.

Figure 9 shows a similar plot for the Medicine Hat-Inuvik 1974-75 data, using latitude in place of altitude. Once again, abrupt breaks occur. In the case of the thawing index, the first break occurs at the boundary between the forest and agricultural zones near Edmonton and again in the Lower Mackenzie Valley. The data were corrected for the effects of elevation above sea level but the changes in slope of the lines remained. The only modification encountered was that the change of slope for the stations along the Lower Mackenzie Valley moved so as to approximate the position of the tundra-forest boundary and the commencement of the slope to the Arctic Ocean.

The freezing index is even more complex, showing breaks near the tundra-forest boundary and the Arctic Ocean, as well as near Lesser Slave Lake and the Hanna-Drumheller area. The latter is the boundary between the

FIG. 6. Weather station data for 1974 and 1975 along traverses from Medicine Hat (MH), along the parallel to Plateau Mountain (PM) and north-northwestward to Inuvik (I), plotted on freezing-thawing index diagrams. Note the abrupt changes in the lines, indicating changes in lapse rate.
agricultural zone and the badlands along the Red Deer River.

If vegetational boundaries are critical, we should re-examine the thawing index data for the Medicine Hat-Plateau Mountain traverse. Figure 10 shows an alternative interpretation of the data with breaks at the boundaries of the treed zone. The lines fit the data points much better but obviously we need more information. An extra four weather stations have recently been added to this traverse in the zone above 1500 m to determine which (if either) of the interpretations is correct.

The major point remains: abrupt changes occur in near-surface lapse rates at certain specific boundaries which are often related to vegetation cover. These boundaries are different in summer and winter. Troll (1943) examined data for South America which showed similar breaks but he missed them by concentrating on frequency of freezing and thawing.

Recently Fuji and Higuchi (1976) have noted similar changes in lapse rates in Nepal. Fuji concluded orally at Edmonton in July, 1978 that the permafrost in the ground might cause the large increase in lapse rate above the permafrost level on mountains. However, this is unlikely for three reasons. First, the supply of heat from the ground is up to three orders of magnitude smaller than the radiation received from the sun, apart from advection by air masses. Second, similar breaks occur below the permafrost boundary and in non-permafrost areas in lowlands. Third, the most obvious break occurs below the permafrost level on mountains. This possible cause is under further study, but the fact remains that a change in vegetation cover can produce an instantaneous change in mean annual temperature and near-surface lapse rate. At Plateau Mountain, the change from forest to alpine zone appears to be accompanied by a drop in MAAT of 2.5°C, caused by the increase in the lapse rate in winter.

CONCLUSIONS

For stations with less than 50 cm of snow cover from December to March in the Northern Hemisphere, the permafrost zones are defined by the long term averages for freezing indices and thawing indices as in Figure 5. Given these meteorological indices, the probability of finding permafrost can be estimated. This relationship fits the data from Norway, Iceland, the People's Republic of Mongolia, and from Canada.

The boundary of the continuous permafrost zone crosses the isotherms for MAAT, explaining much of the con-
conflicting evidence from different areas that has been described in the past. The outer boundary for the discontinuous permafrost zone lies on the cold side of the 0°C MAAT isotherm. There is also a broad zone of sporadic permafrost characterized by patches of ice beneath ponds and in peaty deposits which occupy a similar thermal zone to that of scattered ice caves.

Although most studies of palaeoclimatic change assume a constant lapse rate everywhere, there are some marked variations from one environment to another. The most
marked occurs above the tree line where the lapse rate increases very substantially in winter, though not in summer. This produces a change of MAAT of 2.5°C on Plateau Mountain. The lapse rates in summer and winter behave independently, so that the MAAT averages and partially camouflage the changes. The changes in lapse rates also occur at some points in non-permafrost areas and it appears likely that they are due to spatial and seasonal changes in albedo.

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