The Barrow Urban Heat Island Study: soil temperatures and active-layer thickness

A.E. Klene
University of Delaware, Newark, Delaware, USA

K.M. Hinkel
University of Cincinnati, Cincinnati, Ohio, USA

F.E. Nelson
University of Delaware, Newark, Delaware, USA

ABSTRACT: Several lines of evidence indicate that air and soil temperatures have been modified by the growth of the village of Barrow in northern Alaska through the 20th century. Changes in the Arctic climate may impact local permafrost profoundly, thereby affecting hydrology, soil stability, and infrastructure, including roads, buildings, and water, gas and oil pipelines. Recognition of a potential heat island led to the initiation of a five-year project, begun in summer 2001, to document air temperatures, soil-surface temperatures, and active-layer thickness at 60 locations over an area of 100 km². Temperatures and thaw depths are recorded throughout the central business district, in the growing suburbs, and on the undeveloped tundra. Results from the first summer’s measurements of soil temperatures and active-layer thickness in different land-cover categories within the village and in the undisturbed tundra indicate that surface temperatures and active-layer thickness are generally greater in developed areas.

1 INTRODUCTION

Residents of Barrow, Alaska, have long believed that temperatures recorded in town at the National Weather Service (NWS) site are higher than those at the Climate Monitoring and Diagnostics Laboratory (CMDL) several kilometers outside the urban area (Fig. 1). Several factors indicate that a heat-island effect may exist in Barrow, including the existence of heat islands elsewhere in the high latitudes, expansion of infrastructure accompanying a large increase in population in Barrow since the early 1900s (from several hundred to almost 4000 residents), and consistently earlier snowmelt in the village (ten days in the 1990s) than on the surrounding tundra (Stone et al. 2001).

A heat island in Barrow could have significant impacts on soil temperatures and the depth of thaw within the village. The active layer is important for engineering purposes, and almost all of the biogeochemical and hydrological processes in the terrestrial Arctic take place within it. Changes in the ground thermal regime could result in damage to infrastructure and require changes in building and engineering practices. Maps of thaw depth have been created for some remote regions (e.g. Nelson et al. 1997, Shur & Slavin-Borovskiy 1993), but few for urban areas, even though this is a critical factor in the design of roads, buildings, pipelines, and other elements of the infrastructure. Thermal disruption may be more widespread in Arctic settlements than previously thought.

Steady increases in the number of people living and working in the Arctic strengthens the need for improved understanding of the impacts of human occupancy in this complex environment. The Barrow Urban Heat Island Study seeks to document the spatial distribution of air and soil temperatures in the village of Barrow and the nearby area. Between June and August 2001, sixty sites were instrumented (Fig. 1).

2 BACKGROUND

2.1 Arctic heat islands

Although the concept has been discussed for more than 150 years (Howard 1820), the term “urban heat island” was first used in the 1950s, when Manley (1958) used it to describe local differences in air temperatures between urban centers and surrounding landscapes. While a substantial body of literature (Landberg 1981) exists on heat islands in temperate and tropical climates, cold-region heat islands have received comparatively little attention. However, heat islands have been documented in urban areas of the high northern latitudes, including Alaska (Benson et al. 1983, Bowling 1986, 1991, Magee et al. 1999), Canada (Hage 1972, Woo & Dubreuil 1983), Sweden (Barring et al. 1985), Finland (Heino 1999), and Iceland (Steinecke 1999).

Several anthropogenic modifications contribute to the heat-island effect, mainly by changing the energy balance rather than through introduction of supplemental heat (Landberg 1981). In the Arctic, the increase in the number of buildings that intercept the low-angle...
light and increased airborne particulates relating to activities such as road maintenance, are primary products of human settlements (Dutton & Endres 1991). Dust from both natural (i.e. riverbeds) and anthropogenic sources (i.e. roads) can affect snow-cover, soil properties, and atmospheric characteristics. Dust accumulating on top of snow changes the albedo and thermal conductivity, leading to an earlier melting date unless it accumulates to a thickness of more than 0.5 cm (Drake 1981). Changes to hydrology, either from natural processes (Mackay & Burn 2002) or human engineering (Walker et al. 1987), may also result in substantial differences in the ground thermal regime. Changes in the energy balance, including air temperature, insolation received at the surface, and albedo, affect soil temperatures and thaw depth. Climatic warming of the magnitude predicted by general circulation models could influence this balance further.

2.2 Soil-surface temperatures

Soil-surface temperature and active-layer thickness in permafrost regions are direct consequences of the energy balance, and are determined by complex interactions between air temperature, insolation, wind speed, topography, soil properties, soil moisture, vegetation, and snow cover. Although several studies have examined the effects of clearing natural vegetation and of gravel and paved roads on the active layer and upper permafrost (e.g. Linell 1973, Cole 1998, Esch 1989), few have observed changes over extended periods.

Several studies near Barrow have direct bearing on the present project. Owens & Harper (1977) studied thaw progression and soil temperatures along the gravel seashore southwest of Barrow, and found that the upper beach and mid-spit berms thawed rapidly after snowmelt, which occurred five to ten days earlier than on the nearby tundra. The gravel used in the construction of roads and building pads in Barrow is the same material found on the beaches. Stone et al. (2001) documented increasingly earlier snowmelt in the village than on the surrounding tundra. Reports of earlier snowmelt on barrier islands occurring at rates comparable to those in town and faster than those on the tundra (G. Dvioky, pers. comm. 2001) support the idea that material composition is a primary cause of such differences.

Roads are plowed throughout the winter and subject to direct insolation earlier in spring, which may enhance
such effects. Earlier snowmelt lengthens the duration of the summer season and allows more heat to reach the ground surface and be transferred into the ground to thaw subsurface ice. Whether due to use of gravel for construction, plowing of roads, or dust from other activities, enhanced thaw can have serious repercussions on engineered structures.

Previous work in the area by Ng and Miller (1977), and MacLean and Ayres (1985) demonstrated the importance of land cover type on soil temperatures, while Hinkel et al. (2001) discussed the importance of nonconductive heat transfer. Nelson et al. (1998) compared active-layer thickness measurements from the 1960s and 1990s on the BEO (Barrow Environmental Observatory). Hinkel and Nelson (in press) demonstrated a close relation between topographic concavity, soil moisture, and active-layer thickness at several locations in north-central Alaska.

3 STUDY AREA

3.1 Regional setting

Barrow lies on the coast of Alaska, at 71°N, 156.5°W. The village itself is approximately 15 km southwest of Point Barrow, which divides the Chukchi and Beaufort Seas. The flat coastal plain stretches southward for 100 km before it reaches the foothills, and the Brooks Range lies another 100 km farther south.

The sun remains above the horizon at Barrow from 10 May until 2 August, and remains below the horizon from 18 November through 24 January. This contributes to Barrow’s extreme climate, which is nonetheless moderated by the town’s coastal location. Maritime effects from the Beaufort and Chukchi Seas are large factors in Barrow’s climate, and vary according to the dominant winds. Seasonal variation in temperature in ocean waters is greater than daily changes (Geiger 1966).

During summer the Arctic Front forms south of the northern coast of Russia and Alaska (north of the Brooks Range) and dips into central Canada. In winter the front extends through central Alaska, south along the mountains of British Columbia and along the U.S.-Canadian border and up the eastern coast of North America (Barry 1967).

The dominant wind direction at Barrow is from the northeast. Moritz (1979) suggested that while synoptic-scale geostrophic winds are much stronger in winter than summer, the observed land-sea temperature gradient near Barrow contributes to similar surface wind speeds during both seasons. A lack of diurnal forcing (due to sea-ice offshore for much of the summer), a lengthy coastline and strong Coriolis force at high latitudes combine to cause a greater along-shore

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Simplified Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet tundra (W)</td>
<td>Marshy areas with ephemeral shallow water and saturated soils</td>
</tr>
<tr>
<td>Moist/wet tundra</td>
<td>Low-centered ice-wedge polygon complexes</td>
</tr>
<tr>
<td>complex (M)</td>
<td></td>
</tr>
<tr>
<td>Moist or dry tundra</td>
<td>Nearly complete species-rich vegetation cover</td>
</tr>
<tr>
<td>(D)</td>
<td></td>
</tr>
<tr>
<td>Moist shrub-rich</td>
<td>Dwarf-shrub dominated often forming a dense mat</td>
</tr>
<tr>
<td>tundra (Sh)</td>
<td></td>
</tr>
<tr>
<td>Gravel (G)</td>
<td>Partially vegetated beach gravels</td>
</tr>
</tbody>
</table>

component than is common in other places. Kozo (1982) documented land-sea breezes along the Beaufort coast east of Barrow.

3.2 Instrumentation

Sixty observation sites were established in the Barrow area for this study (Fig. 1). Approximately thirty of these are within the “urban” area and the remainder are in the undisturbed hinterland. These sites were selected to include a range of land-cover types in the study area.

This high-resolution network relies on small data loggers that can obtain and store thousands of measurements, allowing precision not used previously to study heat islands in any part of the world. Each site is equipped with a 2 m tripod, a radiation shield, and a datalogger. Air and soil-surface temperature are monitored hourly using custom Hobo® Pro dataloggers, produced by Onset Computer Corporation, Pocasset, Massachusetts, designed to monitor temperatures from −50°C to 30°C, just enclosing the minimum and maximum temperatures (−49°C and 26°C) recorded in Barrow. These loggers have a precision of 0.02°C and an accuracy of ±0.2°C near the freezing point.

Air temperatures are measured at the standard screen height of 1.8 m (National Weather Service 1989). Soil-surface temperatures are observed in the soil 5 cm below the base of live vegetation using an external thermistor. Noyle’s (1999) vegetation types for the Barrow area (Table 1) were used for initial land-cover classification in August 2001. “Urban” categories were defined based on Noyle’s vegetation classes for the area, but occur within 25 m of an anthropogenic feature.

Measurements of active-layer thickness are made at each of the tripod locations by direct probing of the soil (Mackay 1977). This approach is not reliable for measuring thaw beneath gravel roads or buildings constructed on thick sand or gravel pads. However, this
was attempted at each location, as other methods (i.e. ground penetrating radar) that could be used over large areas do not provide a resolution comparable to probing. Thermal monitoring provides comparable resolution but requires installation of instrumentation at each location.

4 RESULTS

All results discussed here are based on temperature data gathered between 23 June and 11 August 2001, a 50-day period for which data were available from 54 sites installed in June. Several additional sites were added in August to provide better sampling with respect to land-cover categories. End-of-season active-layer thickness was measured in mid to late August. Preliminary analysis of summer 2002 measurements suggests similar results.

4.1 Air and soil-surface temperatures

Figure 2 shows the distribution of mean daily air temperature, grouped by vegetation type. Average values are similar in all of the land-cover categories. The small variability in the “urban” land-cover classes reflects the small size of the urban area and the strong spatial autocorrelation associated with the temperature field in this relatively small area. Indeed, variability was less than expected given the wide array of microsite variability between buildings and near infrastructure. Persistent northeast winds may prevent formation of warm pockets of air during summer, even in the urban center. Outside the village a larger range is found, reflecting a well-defined gradient between cooler coastal and warmer inland sites.

In contrast, the mean daily soil-surface temperatures (5 cm depth), shown in Figure 3, reveal a pattern of much warmer temperatures in the urban land-cover categories. Higher mean values and increased variability are found in the urban version of each vegetation class. The outlier in the urban gravel group is the only instrumented site at which moss was growing atop the gravel pad. This aberration occurred in a sheltered area between two wings of a building, where snow may accumulate preferentially and melt later than the rest of town. This provides an interesting contrast to the other gravel pads in town, which are plowed.

4.2 Active-layer thickness

Examination of active-layer thickness by land-cover categories reveals distinct differences between urban and rural areas (Fig. 4). In urban areas, sites with the same vegetation type as on the outlying tundra showed increased thaw of 25 to 55 cm; in three of four cases, the active layer was twice as thick in the urbanized area. Two outliers were found, one in urban gravel (discussed above) and another in dry or moist tundra. The dry/moist site was at the crest of a very shallow slope leading to a slough. This site may be wind-scoured, with a relatively thin snowcover.

These results show striking correspondence with those from earlier modeling work. Outcalt & Goodwin (1980) used daily weather data to model date of snowmelt and maximum active-layer thickness and to examine the potential impacts of different surface
modifications on the date of snowmelt and thaw depth over a 5 year period. They investigated three zones: the most developed had a 2 m gravel and asphalt pad, snow removal, and building heights of 2 m; an intermediate zone had decreased snow albedo due to road dust and building heights of 2 m; and the least-affected (outer) zone had decreased snow albedo from dust, but no other modifications. Their results predicted an increase of active-layer thickness of more than 60 cm in the first zone, although this increase was contained within the pad itself and did not affect the underlying surface. Zone 2 showed an increase of approximately 10 cm, while the outer zone showed an increase of 35 cm.

The improved resolution of a new digital elevation models available in 2003 may also allow estimation of the thickness of the gravel pads underlying many of the urban sites. Efforts are also underway to map active-layer thickness using the n-factor-based technique described in Klene et al. (2001b). This will allow the relationship between snowmelt, soil-surface temperatures and land-cover to be examined more precisely and more thorough comparisons to be made with the results of Outcalt & Goodwin (1980).

5 CONCLUSIONS AND FUTURE RESEARCH

Differences in active-layer thickness of 25 and 55 cm were found between comparable vegetation classes in urban and rural settings. These occurred even though air temperatures were similar across the study area. The mechanism causing these differences is the focus of ongoing research. Earlier snowmelt, decreased albedo, and physical alteration of the landscape are being considered.

Other research is continuing under the Barrow Urban Heat Island Study. These include time-series analysis of air temperature data from the CMDL and NWS stations, analysis of soil-surface temperatures and n-factors (Klene et al. 2001a), mapping of the daily and seasonal air-temperature fields (Hinkel et al. 2003), and examination of the temperature gradient between Barrow and Atqasuk, a village 100 km south.

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