APPLICATIONS OF THEMATIC MAPPER THERMAL INFRARED IMAGERY FOR PERMAFROST AND TERRAIN STUDIES, RICHARDS ISLAND, N.W.T.

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Abstract

Landsat Thematic Mapper digital data have been used to study permafrost and terrain conditions in the vicinity of Richards Island, District of Mackenzie, N.W.T.. Thermal infrared radiance data were correlated with other bands and ground information in order to study the relation between spectral signatures and various terrain characteristics. Variations and trends in field data suggest that elevation, surface material, ground surface temperature and vegetation have a significant influence on thermal radiance values. Results suggest that Landsat Thematic Mapper data can be useful for delimiting surface and near-surface thermal trends for both regional and site specific applications.

Résumé

On a utilisé des données Thematic Mapper de Landsat pour l'étude du pergélisol et autres conditions du terrain des environs de l'île Richards dans le District du Mackenzie, T.N.-O. Les données de radiance dans l'infra-rouge thermique ont été corrélées avec les autres canaux T.M. et des données de terrain pour l'étude de la relation entre les signatures spectrales et différentes caractéristiques du terrain. Les variations et les tendances régionales des données de terrain montrent que l'altitude, la nature des matériaux de surface, la température du sol et la végétation influencent de façon significative les valeurs de variance thermique. Les résultats obtenus suggèrent que les données Thematic Mapper de Landsat peuvent être utilisées pour déceler les variations thermiques régionales à la surface et près de la surface du sol ainsi que pour des applications ponctuelles.

Introduction

With advances in satellite technology and processing of remote sensing images it has recently become possible to apply satellite derived data to relatively small scale geological studies. In particular, the launch of Landsat IV and V satellites with their Thematic Mapper sensors have heralded a new era, providing very sensitive multi-band data in a digital format at a relatively low cost. In addition to standard visible bands with a resolution of 30 m, the Thematic Mapper sensors have several infrared bands including a thermal infrared band with a resolution of 50 m which is capable of discriminating variations in thermal radiation from the earth's surface. This multi-band capability combined with advances in image processing techniques holds great potential in permafrost areas where surficial sediments may display highly variable geothermal character.

This paper provides an overview of a pilot study undertaken in 1989 to review the utilization of the thermal infrared band of the Thematic Mapper for permafrost and terrain studies in the vicinity of Richards Island and the Mackenzie Delta. This area was chosen for the study since it is known to be characterized by a diversity of surficial materials, vegetation cover and permafrost conditions.

Regional geology

Surficial geology

The study area lies within three physiographic regions (Rampton, 1988); the rolling coastal plain of the Tuktoyaktuk Coastlands, the extensive estuarine delta complex of the Mackenzie River and the broad upland area of the Anderson Plain termed the Caribou Hills (Figure 1). Terrain conditions including surficial sediments, hydrology and vegetation are quite unique in each area.

The Tuktoyaktuk Coastlands are dominated by thick sequences of unconsolidated sediments of various ages and origins. The area is covered with many lakes some of which, located near the coast, have been inundated by the sea as a result of a continuing relative rise in mean sea level (Hill *et al.*, 1985). Elevations are generally less than 60 m, however the area is often rolling, typically with lakes being indented into the surrounding terrain. In the vicinity of Richards Island surface materials are dominated by a sequence of glacial till and glaciofluvial sediments in the south and a discontinuous cover of glacial till on top of fluvial and eolian sands in the north. Vegetation varies from open tundra in the north to shrub tundra in the south.

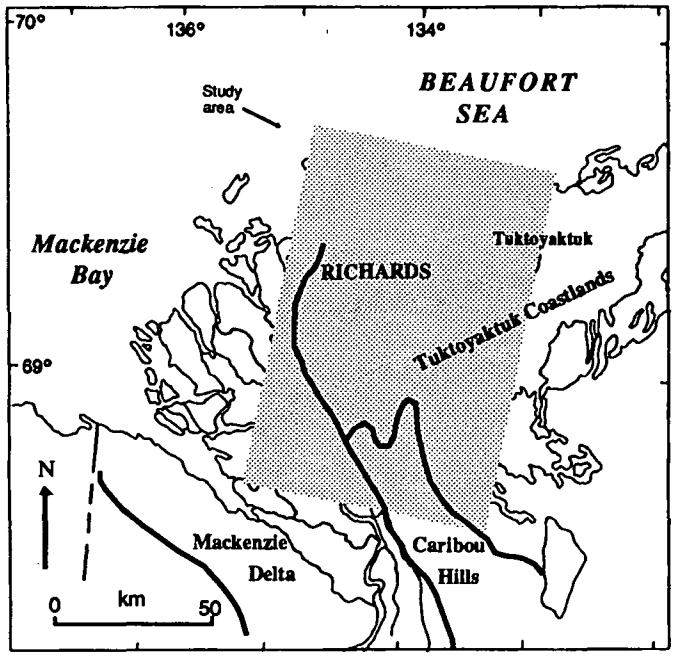

Figure 1. Location of study area.

The modern Mackenzie River Delta is made up of recent fluvial/deltaic silts with a complex network of anastomosing channels and shallow delta lakes. In the in the area of the delta due west of Richards Island (Figure 1), modern deltaic sediments lie directly over eroded sediments of the Tuktoyatuk Coastlands. Vegetation in the delta varies from outliers of trees in the south to barren alluvium and short grasses and sedges in the north. Nearly all of the delta plain is susceptible to flooding during spring breakup or during major storm surge events. Saturated surface conditions prevail throughout much of the summer.

The Caribou Hills are a bedrock dominated upland which reaches over 250 m in elevation. The west side of the hills are characterized by a steep escarpment with deeply incised erosional channels, the east and north flanks of the hills are more gentle. In general, unconsolidated deposits are relatively thin however in some areas Tertiary bedrock composed of unindurated gravels is exposed (Rampton, 1988). Near surface materials are generally well drained with fewer lakes than either the Tuktoyaktuk Coastlands or the Mackenzie Delta. Vegetation cover is highly variable with open tundra in exposed upland areas and with full tree cover in some areas towards the Mackenzie River valley.

Permafrost

An extensive data base documenting permafrost conditions is available from geothermal measurements made in abandoned oil wells throughout the study area (see Judge et al, 1987). These data indicate that permafrost thickness in the Tuktoyaktuk Coastlands and the Caribou Hills varies from 500 to 700 m in northern and central areas to less than 200 m in southern areas. Two permafrost regimes are encountered in the Mackenzie Delta area. In the northeast part of the delta, where outliers of older Pleistocene sediments of the Tuktoyaktuk Peninsula occur at the surface or at shallow depth, possible relict permafrost in thermal disequilibrium may be over 500 m thick. In other areas of modern deltaic sediments, permafrost is typically less than 100 m deep.

Methodology

IMAGE PROCESSING

The remote sensing analyses carried out in this study are based on two Landsat V, Thematic Mapper scenes taken on June 21 and July 23, 1986. These scenes, recorded on computer compatible tapes, were registered to one another in order to compare the evolution of the spectral signatures between early and mid-summer. A major emphasis was placed on the thermal infrared band (Band 6) with a designated wavelength of 10.4 to 12.50 µm. In general, minimal processing was undertaken on the original data (such as geometric corrections) since smoothing algorithms tend to alter the digital count values introducing significant variations especially when high temperature gradients are involved (Wukelic *et al.*, 1985). No correction was applied to the thermal radiant values since the relative temperatures were considered to be more significant in this study than absolute values. As pointed out by Wukelic *et al.* (1985), empirical calibration curves established by ground data (lake temperatures) seem to be more valuable than conventional adjustment methods involving complex calibrations.

Data processing and image generation for this project were carried out entirely with a micro computer, with custom in house software. For display purposes in this report, colour plots were hand contoured to produce an accurate grey scale representation of the colour images (Figures 3 and 4).

In addition to the thermal infrared imagery, several other bands were investigated. Of particular interest was imagery produced by plotting the ratio of Band 4 ÷ Band 3 to produce a Biomass index (Tucker 1979). Similar work is reported by Tornocai and Kristof (1976) using Landsat MSS data. A close relationship has been shown between vegetation cover and the nature of surficial materials in other permafrost areas (Edlund, 1982).

Field program

In order to provide detailed data on surface conditions in the study area an extensive ground truth program was carried out during the first two weeks of July, 1989. During the ground truth program, a helicopter was used for transportation with a total of 92 stops along 4 transects (Figure 2). A major emphasis was placed on completing transects across major boundaries identified on the thermal infrared images. Data collected at each stop included: lake surface temperatures, thaw depth (and variability in depth), elevation, drainage, surface sediment type and vegetation characteristics. This information was compiled in a spread

Figure 2. Sample (ground truth) locations map. Squares correspond to stop sites and ellipses indicate ground temperature sites.

sheet format along with pixel values for each band from the June and July images.

A vast amount of other background information concerning terrain conditions and ground temperatures, were also available for this study from other regional investigations of permafrost and surficial geology undertaken by the authors and from unpublished information made available by other scientists of the Geological Survey of Canada.

Review of June and July images

The June and July images shown as Figures 2 and 3, are based on radiance values for terrestrial areas of the study region. As discussed previously, it should be noted that thermal radiance values, shown on the figures, have not been corrected and therefore only the relative trends in the images can be compared. From this perspective the images show similar trends with the lowest radiance values being

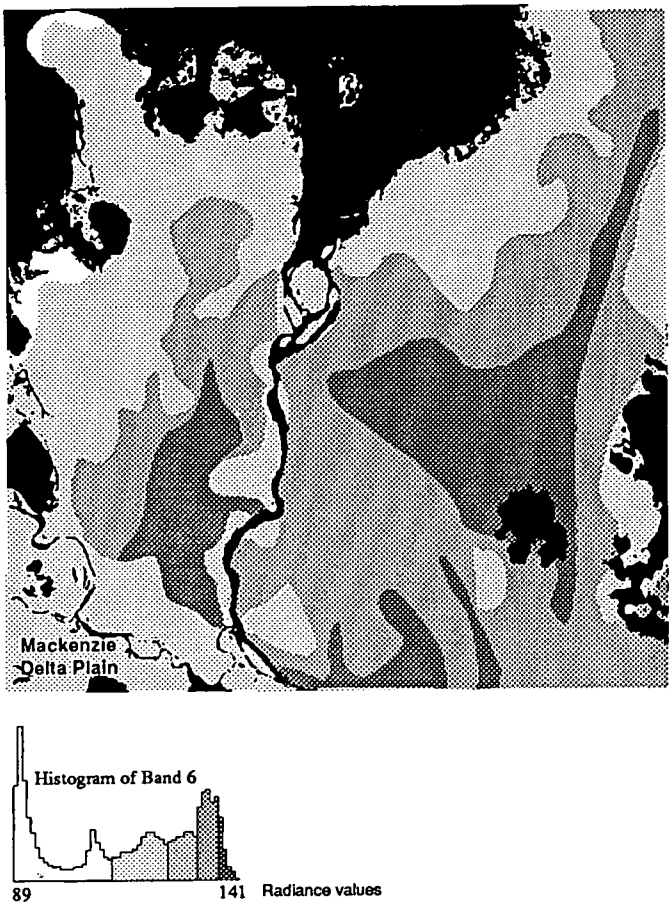

Figure 3. Isothermal map of Landsat T.I.R. data for June 21, 1986.

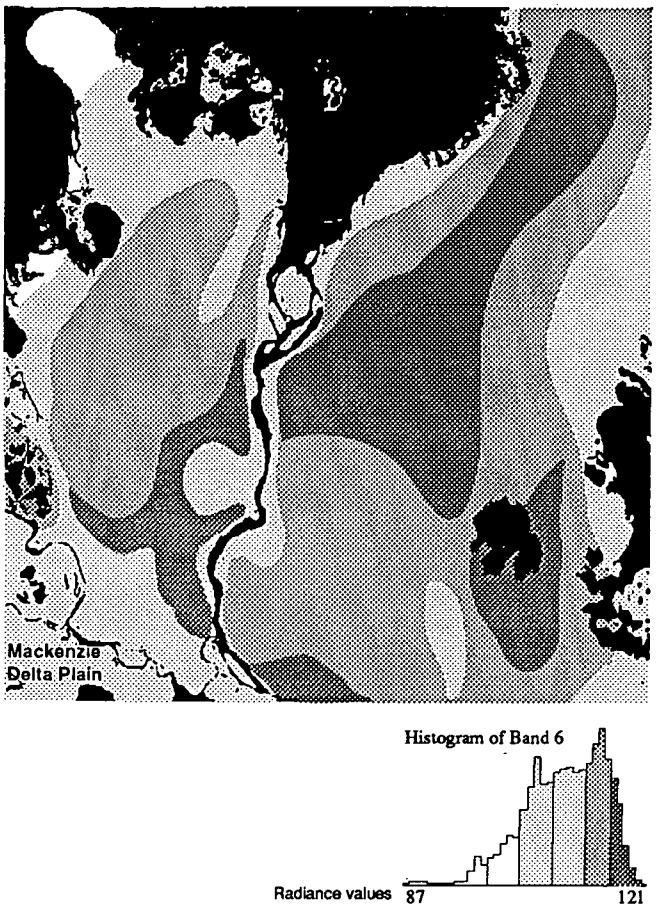

Figure 4. Isothermal map of Landsat T.I.R. data for July 23, 1986.

associated with a coastal fringe bordering the Beaufort Sea, the vicinity of the active Mackenzie Delta and the east channel of the Mackenzie River. The central area of the Tuktoyaktuk Peninsula and Richards Island show sharp gradients, with a trend to higher radiance values towards the centre of the peninsula and towards southern Richards Island. This trend persists from June to July on Richards Island, however, the zone of highest radiance on the Tukoyaktuk Peninsula shifts further north in the July image.

In addition to the terrestrial data discussed above, the coloured versions of June and July images showed considerable variability in the radiance character of surface water throughout the study area. June and July data yielded spectacular discrimination of the warm plume of Mackenzie River water as it entered the Beaufort Sea with very low radiance values being associated with the colder ocean water. Many of the lakes also showed considerable variation in thermal radiance values.

Discussion

Surface water temperature

Since the surface water bodies occurring in the study area showed considerable contrast in thermal radiance values, part of the ground truth program was devoted to collecting surface water temperatures. This also provides a good method of evaluating the accuracy of thermal radiance data since a direct relationship should exist between the two data sets.

In total, data from 32 lakes were collected from the mainland of Richards Island and shallow lakes on the Mackenzie Delta. In addition, one measurement was made of surface water flowing in the East Channel of the Mackenzie River. Since there was a considerable amount of lake ice still covering many of the lakes in the area on the date of the June image, July data was used for the comparison. Considerable variation in lake surface temperatures were found throughout the study area. The scattergram (Figure 5) shows a definite relationship between surface temperature and thermal radiance, even though field data were not gathered on the same date or year as the Landsat data.

In mid July, based on field and Landsat data, lakes in the delta area and on the mainland of The Tuktoyaktuk Peninsula are warmer with temperatures in the range of 13 to 15 °C while lakes in the vicinity of northern Richards Island are as cold as 8 °C. The thermal effect of warm water flowing into Kugmallit Bay from the East Channel of the Mackenzie River also shows sharp variation in surface temperatures with estimated variation from 15 °C at the mouth of the river to less than 7 °C offshore.

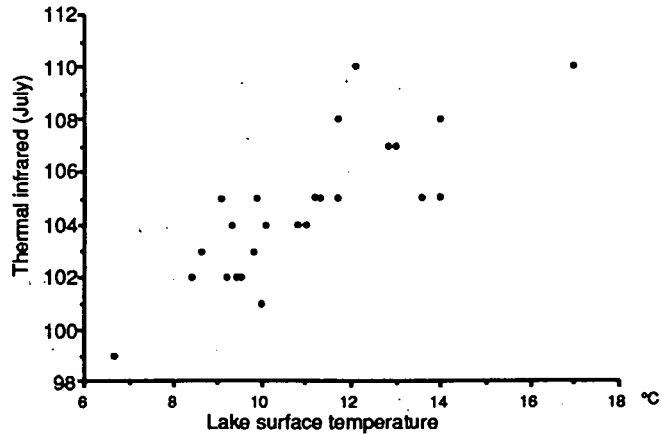

Figure 5. Scattergram of Landsat Thermal Infrared radiance values Vs. Lake surface temperature, July 23, 1986.

TERRESTRIAL TRANSECTS

A number of ground transects were run in the study area to investigate the nature of the trends shown on the thermal infrared imagery. For the purposes of this paper we have chosen to limit our discussion to the Lousy Point transect and Nesbit Lake area (stops 77-80, Figure 2).

Lousy Point

The Lousy Point transect runs for some 40 km across central Richards Island, from Lousy Point on the East Channel of the Mackenzie River to the Beaufort Sea (Figure 2). The terrain along the transect rises abruptly from the East Channel reaching elevations of over 60 m in the first 10 km and then drops gradually to the north (Figure 6a). Lacustrine basins along the transect are typically inset into the upland areas and may be 30 m or more below them. Ground truth sites were chosen to reflect the variation in topography and terrain types along the transect.

The thermal infrared imagery for both June and July show the strong influence of elevation. Thermal radiance values for highland areas close to the east channel are about 118 while values in the north drop to about 108 near the Beaufort Sea (Figure 6b). This trend is apparent regionally (Figure 4) and is consistent even over short distances. For example the radiance values for drained lake sites (eg #31 and 36) are significantly lower than those of the surrounding uplands (eg #34, 37). In some cases it is clear that the relationship may also be influenced by material since the drained lake sites and many of the lowland areas are underlain by lacustrine sediments while the highlands are underlain by glacial fluvial sediments and glacial till. However, since the correlation with elevation persists even if only highland sites are considered, we suggest that the thermal radiance reflects a regional trend of surface temperatures across Richards Island which is elevation controlled. Early July thaw depths verify this thermal trend across the transect with the greatest thaw depths generally associated with the highland sites (Figure 6c). However, as would be expected thaw depth also responds to minor material, vegetation and elevation variance.

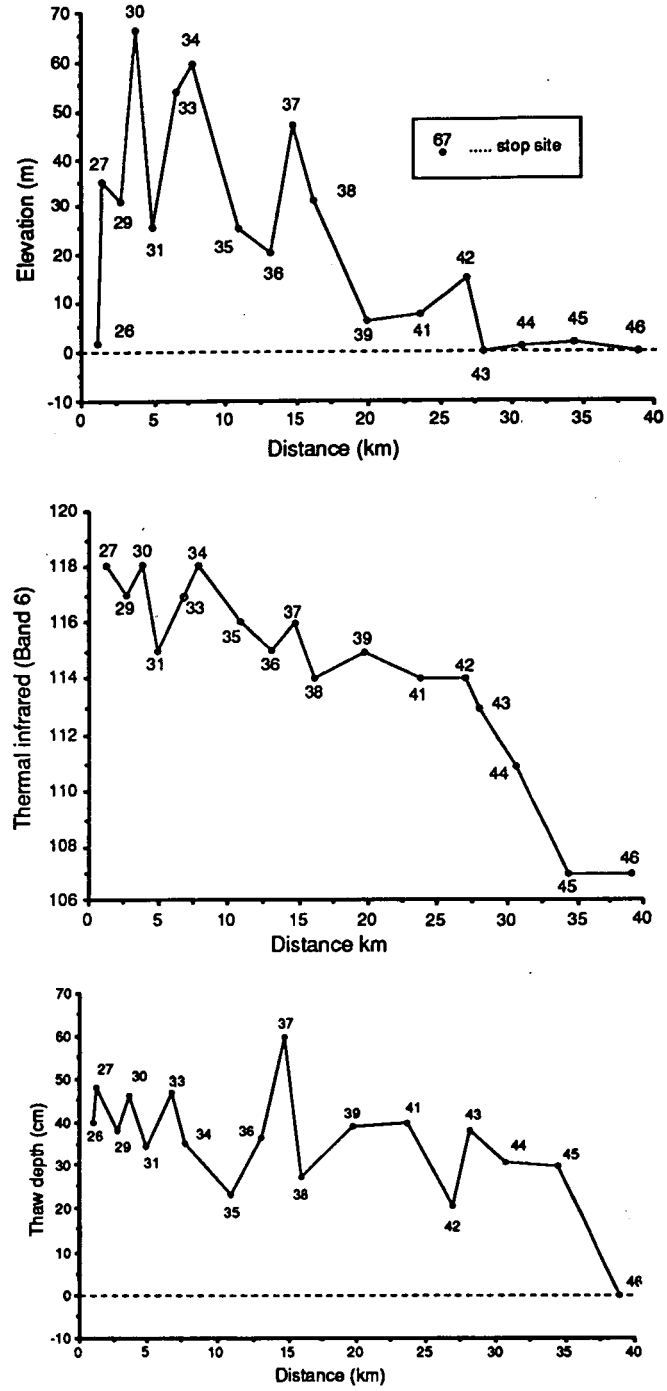

Figure 6. Lousy Point transect:
6a Elevation Vs. Distance.
6b Landsat T.I.R. Vs. Distance (band 6), July 23, 1986.
6c Thaw depth Vs. Distance.

The general trend described here, with warmer conditions being prevalent in the highland areas on first consideration may seem improbable given anticipated adiabatic lapse rates. However this trend is consistent considering the coastal influence of the Beaufort Sea. Cold onshore winds, which occur throughout much of the summer (Harper and Pennland, 1982), typically move across pack ice positioned less than 150 km offshore. This has a dramatic influence on

the coastal climate with the effects generally being mitigated inland. In addition, the cool ocean water often initiates extensive local fog further cooling coastal areas.

Nesbit Lake

The thermal radiance data along the Nesbit Lake transect also show that the highland areas are warmer than the low lying areas. Of particular interest on this transect was a relatively strong contrast in thermal radiance observed over a small area in the vicinity of site 79 (Figure 7). In this case site 79.1 and 79.2 had radiance values of 115 and 120 respectively, even though they were only located some 200 m apart and there was no apparent elevation or morphology change. This contrast is apparently quite real since ground probing on July 6 indicated thaw depths varied from 20cm at 79.1 to 44 cm at 79.2. Pits excavated during the ground truth program revealed that there was an abrupt change in the near surface sediment between these sites from a stony clay till at site 79.1 to a sand at site 79.2. The variability in the thaw depths is likely due to the water content and different thermal properties of these materials.

GROUND SURFACE TEMPERATURES

In an attempt to establish the association of ground surface temperature and thermal radiance values, an estimate of mean annual ground surface temperature was determined for 8 upland sites on Richards Island (Figure 2). Ground surface temperature was estimated by extrapolating deep (50 to 200 m), linear geothermal gradients to the surface for 6 deep instrumented boreholes (Taylor et al, 1982; Judge et al, 1981) and for two shallow 30 m boreholes (Kurfurst, 1987). It is recognized that this provides a very general estimate of mean ground surface temperature. In addition, there are relatively few sites and the ground surface temperatures at a particular site may be expected to vary greatly throughout the year in a complex fashion. However, when mean ground surface temperatures are plotted against thermal radiance

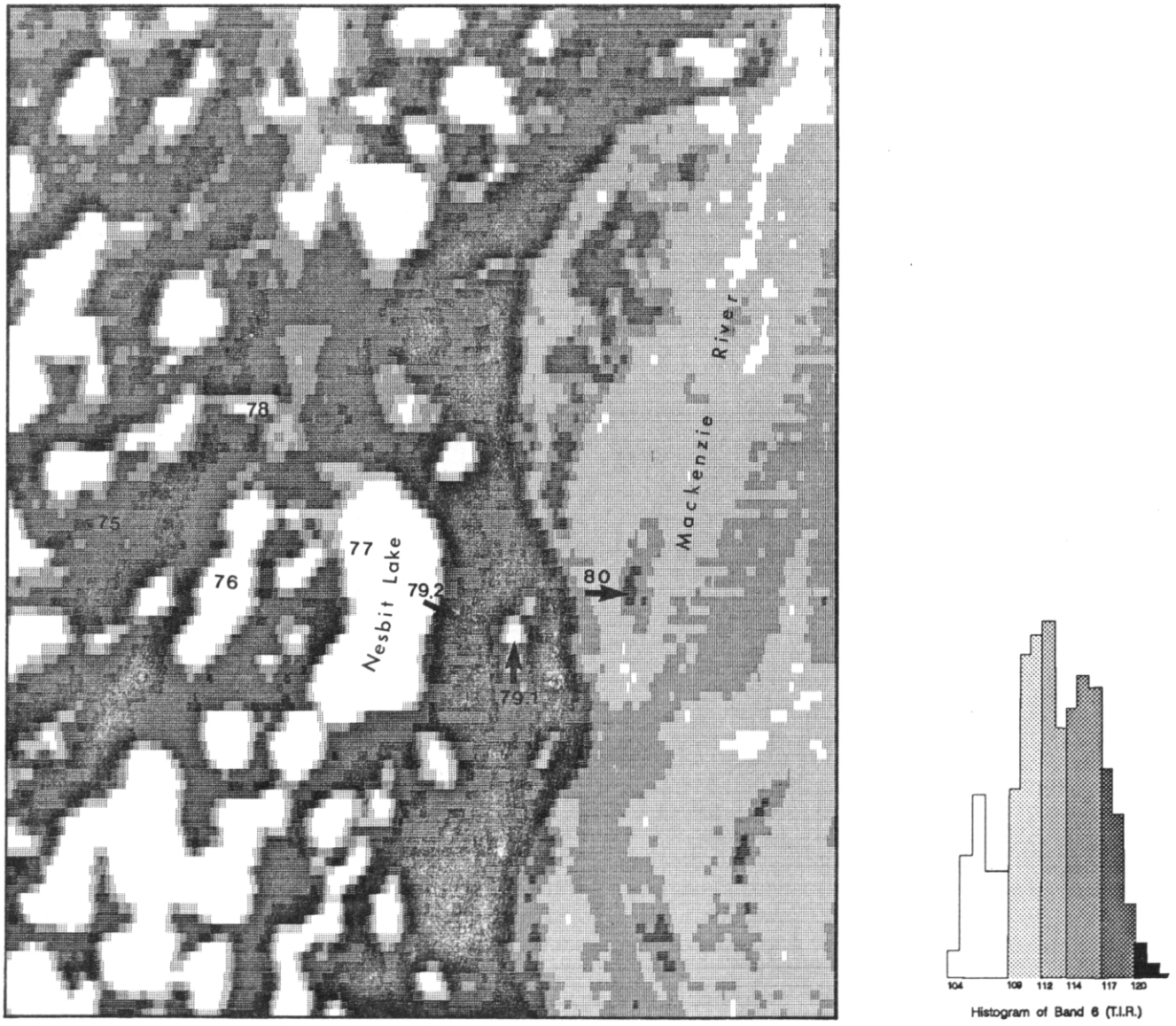

Figure 7. Nesbit Lake area: T.I.R. July 23, 1986 and stop sites July 7, 1989.

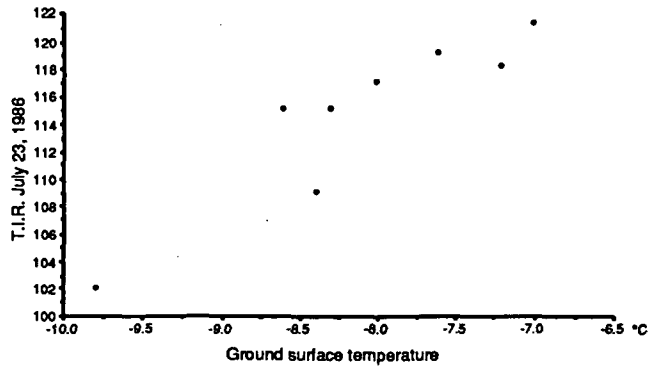

Figure 8. Scattergram of Landsat Thermal Infrared radiance values, July 23, 1986 Vs. ground surface temperatures.

values a surprisingly good correlation is observed (Figure 8). This suggests that the "snap shot" thermal radiance data may be related to longer term, annual trends. Sites which exhibit colder mean ground surface temperatures are also colder on the dates the images were generated. Since the images were processed in summer one may speculate that the summer climatic conditions are important in controlling geothermal variations in this area.

Conclusions

This pilot study illustrates that Thematic Mapper thermal-infrared imagery may be used to quickly define surface and near-surface thermal conditions over relatively large areas. In the vicinity of Richards Island, thermal infrared data allowed discrimination of variations in surface water temperatures of lakes and of Mackenzie River water as it flows into the Beaufort Sea. Terrestrial areas of the Tuktoyaktuk Coastlands showed low thermal radiance values on the coastal fringe along the Beaufort Sea and higher values to the south and towards the Mackenzie Delta. The Mackenzie Delta area itself was generally characterized by low radiance values thought to result mainly from the extensive cover of surface water throughout the area.

Ground surveys on Richards Island showed that thermal radiance zones identified on Landsat images correspond to terrain conditions such as elevation, the nature of surficial material, thaw depth and vegetation. Inland areas are generally higher and appear to experience warmer summer temperatures than low-lying coastal areas. Thermal radiance values were affected by material with areas of sandy soils generally being warmer than areas with fine grained soils but with the trend from the inland areas to the coast still persisting. Detailed observations in the vicinity of Nesbit Lake indicate that these trends exist over relatively short distances in areas with no surface expression of the material change.

Of particular interest in this study was the apparent correlation between radiance values and mean ground surface temperatures derived from deep geothermal data. Areas in the vicinity of northern Richards Island with low mean ground temperatures were found to have low early summer radiance values, while areas of southern Richards Island with higher mean annual ground temperatures were found to have higher radiance values. This relationship is thought to be mainly due to the strong relationship between climate and permafrost conditions in this area. It is recognized however, that in other areas factors such as glacial history, proximity to major water bodies and sea level history may influence the geothermal regime and Landsat T.M. radiance values. The utility of thermal radiance data in all instances is expected to be substantially improved with supportive regional and site specific data.

Acknowledgements

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