

EFFECTS OF AN ARCTIC SETTLEMENT ON THE SNOWPACK

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ABSTRACT

Research was carried out in 1981 to study the effects of a northern settlement on the arctic snowpack. A comparison of the snow cover in and outside the airport area of Resolute in the Northwest Territories shows that

- (1) The snow distribution pattern was affected by the presence of buildings and by snow removal operations.
- (2) The emission of pollutants from dwellings and from the power plant contaminated the snow with trace metals.
- (3) The dust load on the snow was greatly increased within the settlement and this considerably reduced the snow surface albedo.
- (4) With a reduction in albedo, the radiation balance was changed and it was possible to estimate the net radiation as an empirical function of the albedo and the incoming short-wave radiation.
- (5) A contrast in the radiation balance was responsible for an accelerated melt rate near the human settlement.

Field observation and transects extending outward from Resolute showed that the anthropogenic effects diminish sharply away from the human settlement, suggesting that the influences are localized.

INTRODUCTION

The arctic snowpack is considered to be relatively free of anthropogenic influences, except for the minor amount of trace elements transported from the temperate latitudes (e.g. Barrie et al. 1981). While this is true on a regional scale, the presence of human settlements inevitably produces local disturbances in the pristine environment. Such changes are caused by the presence of buildings and local transportation networks, the movement of air and overland traffic, the release of pollutants from power plants and space heating, and in some areas, the practice of mining or other economic activities. The results are a drastic change in the snow distribution pattern (Mellor 1965), a contamination of the snowpack (Murozumi et al. 1969, Weiss et al. 1971), a decrease in snow albedo due to a dust cover (Slaughter 1969) and accelerated snowmelt in and around the settlements (Outcalt et al. 1975).

Most studies have focussed upon individual aspects of the anthropogenic influences upon the arctic snowpack. The present research investigates both the physical and the chemical characteristics of the snow as it is affected by a typical human settlement in northern Canada. The objective of this study is to compare the snow conditions in and outside an arctic settlement by examining the snow distribution pattern, the snow quality, the radiation balance and the melting of the snow.

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STUDY AREA

Resolute (74°45'N, 94°50'W) is a coastal settlement in the Queen Elizabeth Islands, serving as an air transportation centre for the traffic of the Canadian Arctic Archipelago. The airport and its auxiliary buildings agglomerate with other government and commercial buildings to cover an area of about 0.5 km². The native village is located 7 km southeast of the airport and was not included in this study.

The winter residents, numbering about 200, live in oil-heated houses and travel by gasoline-powered vehicles. Electricity is supplied by a diesel-fired generating plant located next to the airport. Throughout winter, snowblowers mounted on trucks keep the runway open to aircraft.

To the east and north of the 2 km airstrip are rolling hills rising from sea level to 250 m (Fig. 1). Recent glaciation has resulted in many topographical depressions, some of which are occupied by lakes. In summer, the ground surface is mostly barren, with surficial deposits that include lithosols, polar desert materials and patchy tundra and bog soils (Cruickshank 1971). These deposits are derived partly from the bedrock of limestone, dolomite and calcareous shale (Thorsteinsson 1958), and partly from materials of alluvial and coastal origin. At the airport and the settlement, the original materials were re-worked or covered by other earth materials to provide foundations for the buildings and the airstrip. Neither the airstrip nor the roads are paved, and when they are not snow-covered, passing traffic often stirs up considerable dust.

Winter lasts for about nine months, during which time the snowpack undergoes little melting. The January mean minimum temperature falls to -36°C. Melting outside the settlement usually commences in June (Heron and Woo 1978) and the bulk of the annual snowfall often disappears in two weeks. Around the settlement, melting is advanced by several days. For this study, a site near the airstrip (airstrip site) was set up to compare the snow conditions with a site (McMaster met. site) located 3 km northeast of the northern end of the runway. The latter site is considered to be relatively free of anthropogenic effects. In addition, this study makes use of data from the government weather station which is adjacent to the southern section of the runway.

METHODS

A pre-melt snow survey of the airstrip site was carried out on May 28-29. Snow depth was measured with a steel rod at 2 m intervals along six transects. Snow density was determined at fifteen points using a Meteorological Service of Canada snow sampler.

At the airstrip site (Fig. 2) three types of snow surfaces were recognized: dirty (with a brown dusty surface), moderately dirty ("caramel" coloured, with some dust visible) and relatively clean snow (white to slightly yellow tinge and with little dust visible). For each type of snow surface, and for the clean snow at the McMaster met. site, duplicate samples were obtained at the end of each day by scraping off the top 20 mm of an area covering 150 x 150 mm², using a trowel and a plastic scoop. This procedure captured virtually all of the surface dust. The dust content of each sample was determined by filtering the meltwater through a pre-weighed Millipore membrane of 0.45 µm pore size. Whenever possible, filtering followed a field procedure outlined by Østrem and Stanley (1969). When the dust content was excessively high, the suspension was left to settle and only the clear supernatant was filtered as described above. The Munsell colour of the wet dust-covered Millipore membrane was noted. The dusty membranes and the bags containing the residue from the very dusty samples were weighed at McMaster University. Some samples were analyzed for grain size distribution by sieving in an Allen-Bradley sonic sifter.

Snow samples were gathered in 1982 at 42 points along a 35 km transect running from the upper reaches of the Bacon River (74°58'N, 94°30'W) through Resolute and out to the sea coast at the abandoned Inuit village. Sampling was achieved by digging a pit well upwind of our transportation vehicles, cutting the pit wall back and taking an integrated sample of the snowpack using a clean plastic scraper and scoop. The samples were dropped directly into clear heavy plastic bags and rapidly melted in the sealed bags. A 500 ml aliquot of each sample was placed in a plastic bottle previously rinsed with 0.1 N nitric

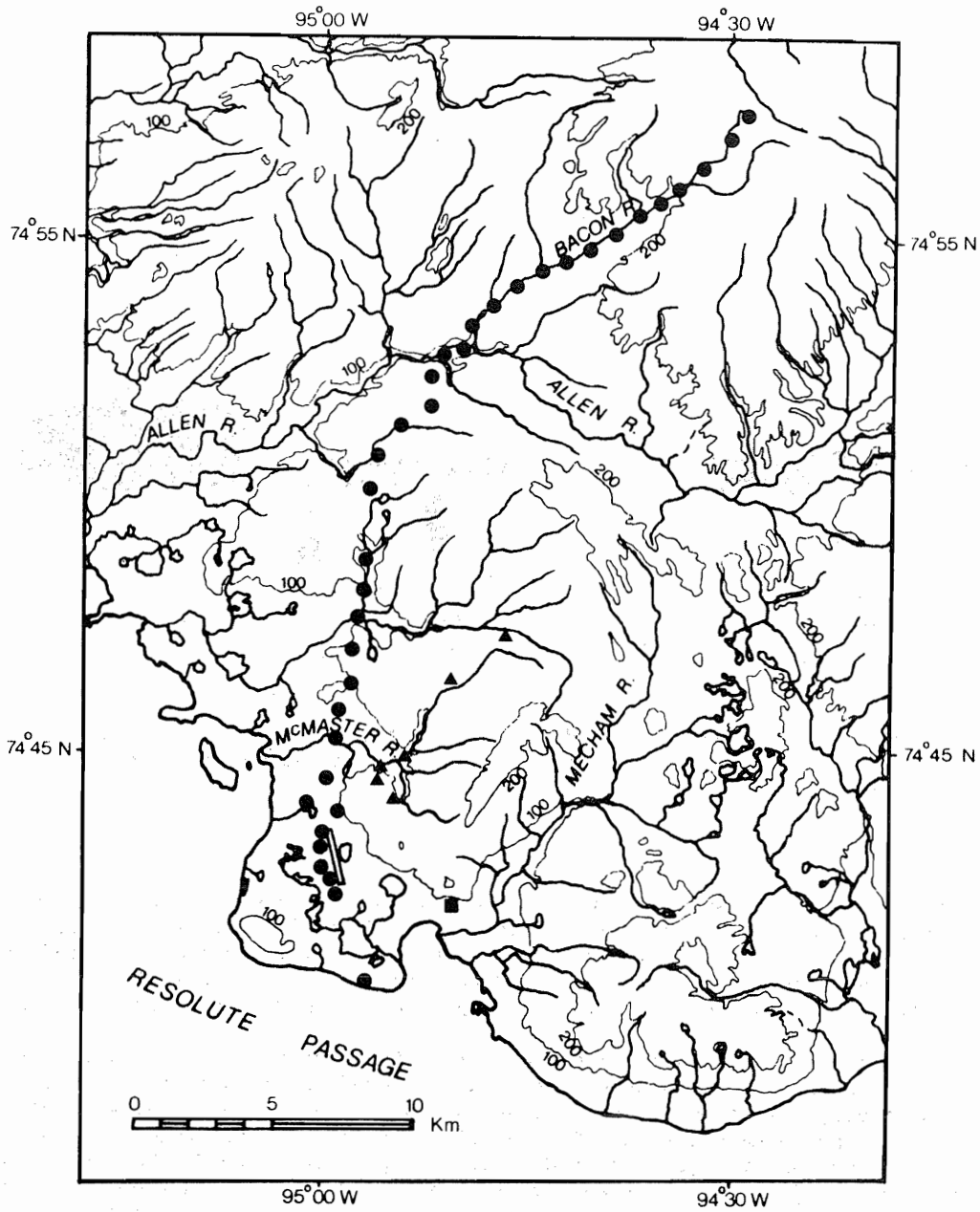


Figure 1. Topography of the study area near Resolute showing the study sites and the snow sampling transects.



Figure 2. Airstrip site showing snow drift around objects and a dirty snowpack. Centre of photograph shows the smoke plume emitted by the power plant at Resolute.

acid and a few drops of the same acid were added. These aliquots were sent to the Ontario Ministry of the Environment, where the concentrations of Al, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Ni, P, Pb, S, Sr, Ti, V and Zn were determined by inductively coupled plasma atomic emission spectroscopy. Electrical conductivity and pH were determined in the field using respectively a Barnstead conductivity bridge and a Cole-Parmer digital pH meter.

Measurement of radiation, air temperature, relative humidity and wind were carried out at both study sites. Net radiation (Q^*) and reflected short-wave radiation ($K\uparrow$) were measured respectively with a Swissteco SW-1 net pyrradiometer and an inverted Eppley Precision Spectral pyranometer, at a height of 1 m above the snow surface. The signals were recorded on Rustrak millivolt recorders after amplification. The hourly $K\uparrow$ values were used with hourly incoming short-wave radiation ($K\downarrow$) data obtained from the government weather station to obtain a continuous record of albedo at both sites. Additional spot measurements of albedo for different snow surfaces were taken using a hand-held, gimbal-mounted assemblage of two Kipp and Zonen CM-5 pyranometers.

Air temperature and relative humidity were recorded on Lambrecht thermohygrographs housed in Stevenson screens, 1 m above the snow surface. Wind speed at 1 m height was monitored by a Casella sensitive cup anemometer whose signals were registered on a Rustrak event recorder. Additional hourly data, particularly atmospheric pressure, were obtained from the government weather station in Resolute. During the melt period, daily ablation was determined at six locations by averaging 15 measurements of the daily change in the distance between the snow surface and a 1 m long wire held taut between two stakes.

RESULTS

Snow distribution pattern

The effect of buildings and other structures upon the distribution of snow has been much described (Mellor 1965). Similar effects were observed in Resolute and will not be discussed except to use the airstrip site as an illustrative example (Fig. 3). The plot is bounded by roads and runway ramps with culverts and ditches to drain the high flows. In late May 1981, the snow surface topography showed some noticeable drifts around two abandoned vehicles, and a deep pack at the western end due to snow removal from the main road. The surface of the snow field was superimposed with sastrugi, dunes and ripples. The microtopography of these features was more pronounced at the airstrip site than at the McMaster met. site located away from town.

The snow-choked ditches and culverts often prevent the drainage of meltwater. Drainage at the airstrip site runs towards the north. Every year in spring, a work crew has to dig out the snow from the ditches along the main road. On June 5 1981, runoff from the ditch spread over the western part of the plot and saturated the bottom of the snowpack. On the same day, water draining through the eastern end was blocked by a snow-filled culvert. The impounded runoff flooded part of the field (Fig. 3) until the early hours of June 9 when the snow blockage in the culvert was suddenly broken. Such a hydrological phenomenon is analogous to the bursting of snow jams in the natural channels nearby (Woo 1979), but is unlike the clearance of culverts in subarctic areas where aufeis, and not snow, prevents meltwater from draining (Grey and MacKay 1979).

Snow chemistry

Most snowpacks contain dust and various trace elements derived from three major sources: oceanic, terrestrial and anthropogenic. Ions of oceanic origin, including Na, K, Mg, Ca and Sr (e.g. Duce et al. 1975), come mainly from sea spray and often lead to an increase in conductivity. Unfortunately, we did not have values for K and Na, but the trend in conductivity shows a landward decrease (Fig. 4). The concentration of Sr confirms the oceanic influence, as it remained above the background level near the coast. Ions of terrestrial origin often include Ca, Fe, Al, Mg, Mn and Ti (e.g. Boutron and Lorius 1979). For Resolute, Ca and Mg are especially prominent because of the local geology. In areas outside of the settlement, average Ca and Mg concentrations were 815 and 390 $\mu\text{g}/\ell$ respectively.

Some of the elements found in the snow and most commonly produced by human activities are Pb, Zn, V, Mn, Cd, Cu and S (e.g. Herron et al. 1977, Shaw 1979, Weiss et al. 1975). In Resolute, the main sources of anthropogenic contaminants are the burning of fossil fuels and the deposition of dust from the runway and roads. At the settlement, fuel combustion produced a sharp peak in S, Pb, Mn, Zn, V, Ni, Ca, Fe, Al, Cr, Co, Ba, Cd and Cu, and the agglomeration of runways and roads led to an abrupt increase in all the elements of terrestrial origin (Fig. 4).

Background concentrations on Cornwallis Island outside of Resolute were up to three orders of magnitude higher than those for most other polar sites (Boutron and Lorius 1979, Herron et al. 1977). Our results were within an order of magnitude to those measured near Barrow, Alaska (Weiss et al. 1978). Exceptions were Ca and Mg which tend to show high concentrations in the snowpack of areas underlain by carbonate rocks (e.g. Herrmann 1977).

Dust cover on snow

A large amount of dust fell on the snow along the airstrip and in the settlement. The colour of the dust ranged from light yellow (2.5 Y 7/3 on the Munsell scale), through dull yellow (2.5 Y 6/3), to yellowish gray (2.5 Y 5/4). About 70 percent of the particles was sand and the remainder was silt and clay. Most of the dust was concentrated at the snow surface. Based on 70 samples collected from the top 0.02 m of the snowpack near the airstrip, the average dust concentration was $56.5 \pm 52.3 \text{ g/m}^2$. This contrasted sharply with the mean concentration of $0.2 \pm 0.1 \text{ g/m}^2$ derived from 40 samples collected at the snow surface at the McMaster met. site. Qualitative observation showed that the surface

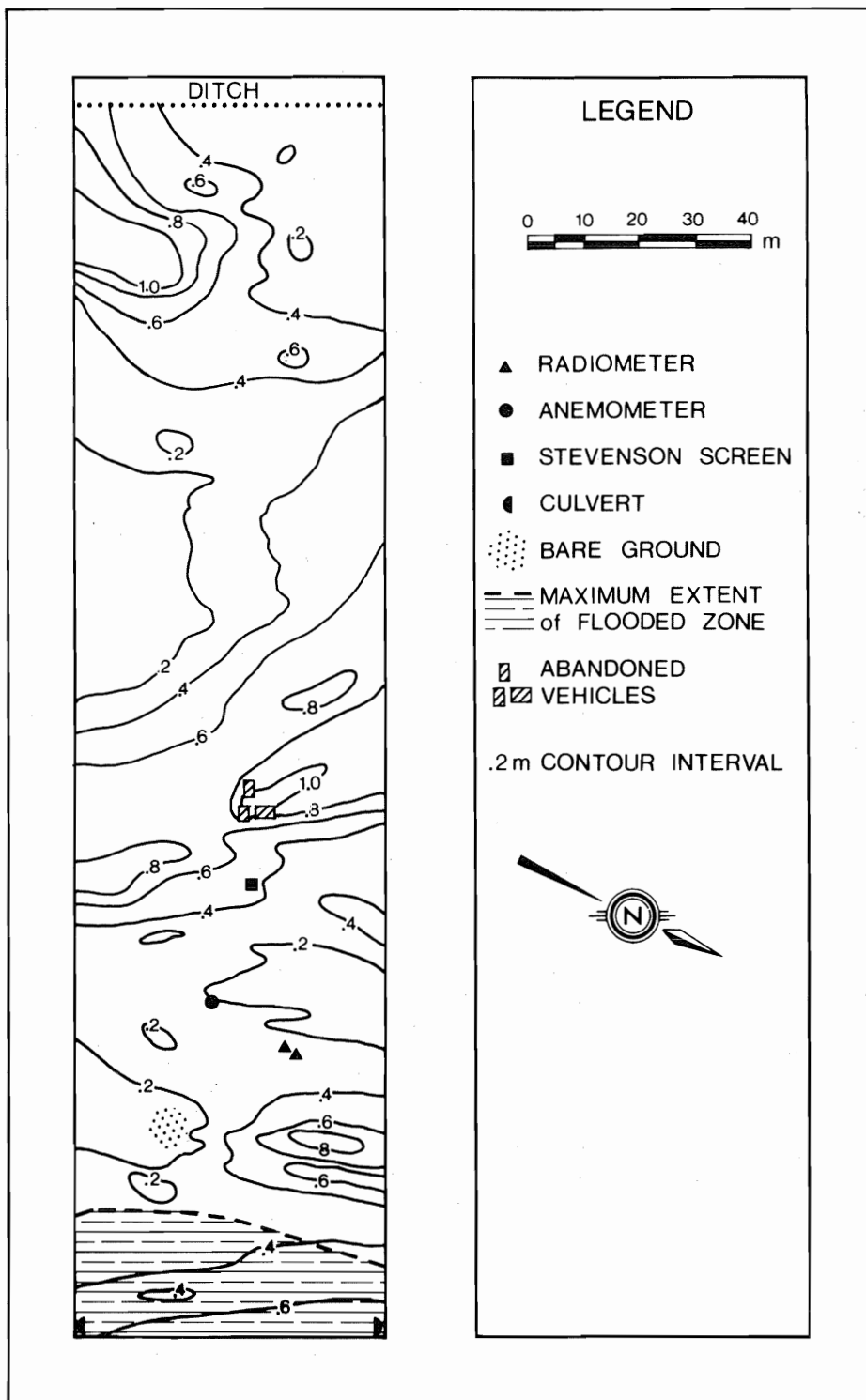


Figure 3. Depth of snow at the airstrip site, observed in late May before melting began. The extent of flooding during the melt season is also shown.

dustiness decreased abruptly about 2 km beyond the northern end of the runway.

The surface dust content at the airstrip site varied greatly within a small area, ranging from 9.3 g/m² for the cleaner snow to 133 g/m² for the very dirty patches. In June 1981, samples were taken from three plots on various days to examine the variation of dust content during the melt season (Fig. 5). The data showed considerable day to day variation due to sampling error and the great spatial variability of dustiness. An increasing trend is evident. For the dirty snow, the dust content rose from 90 to 190 g/m² between June 1 and June 9. Within the same period, the increase was from 25 to 50 g/m² for the moderately dirty snow and from 3 to 18 g/m² for the cleaner snow. For comparison, the increase was from 0.11 to 0.45 g/m² in late June when the snow melted at the McMaster met. site. A tendency for increasing dustiness during the melt season has also been reported by Higuchi and Nagoshi (1977) and Kohno and Maeno (1979). For Resolute, the trend was related to an increasing area of bare ground on the runway, the roads and the hilltops which were the major sources of the dust.

The radiation balance

The decrease in albedo can be quantitatively related to the dust load at the snow surface. Figure 6 shows the relationship between midday albedo and the dust load at the study sites. The form of the curve is comparable to those observed by Higuchi and Nagoshi (1977) for a perennial snow patch and by Peschansky (1963) for sea ice covered with coal dust. The clean snow in Resolute had an albedo averaging 0.75. As the dust load increased, albedo declined exponentially such that for moderately dirty snow with a dust content of 50 g/m², the albedo was about 0.5. Snow albedo fell asymptotically to 0.3, which is close to the albedo of basal ice.

The snow albedo strongly influences the radiation balance, Q*:

$$Q^* = (1-\alpha) K\downarrow + L^* \quad (1)$$

where K \downarrow is the incoming short-wave radiation and L* is the net long wave radiation. In areas where the surface albedo remains relatively unchanged, Davies (1967) found an empirical relationship

$$Q^* = a + b K\downarrow \quad (2)$$

where a and b are regression coefficients. This approach was used successfully by Petzold and Wilson (1974) to estimate the radiation balance over the snow of subarctic Canada. To include the effect of albedo, the data from the airstrip and the McMaster met. site were pooled to yield the equation

$$Q^* = -20.5 + 0.69 (1-\alpha) K\downarrow \quad (3)$$

where the units of radiation are in W/m² and α is midday albedo. The values are estimated for the 12-hour total radiation during the period of 0600 h to 1800 h. At other times of the day, the sun is at a very low angle above the polar horizon, rendering the measurement of albedo extremely unreliable.

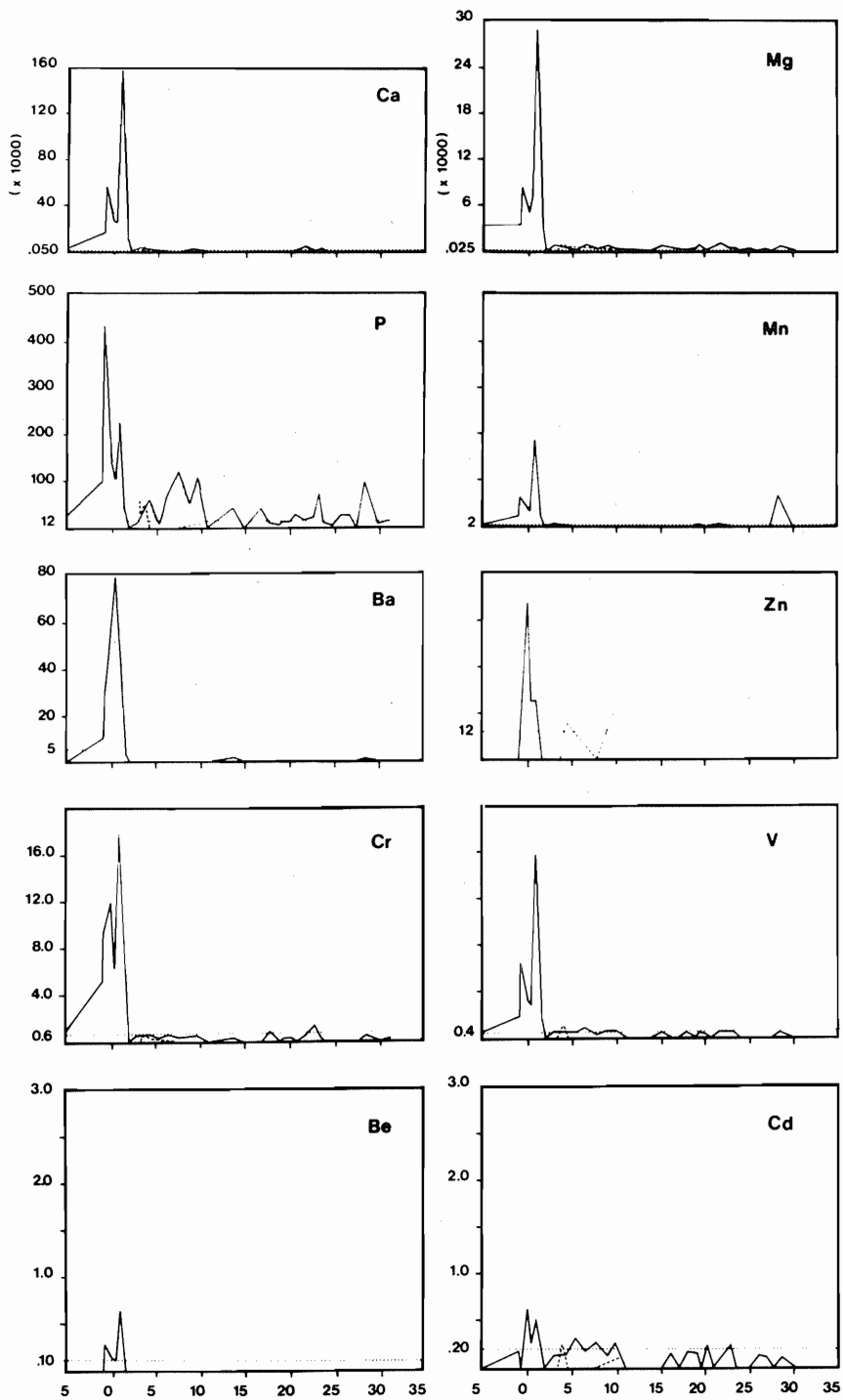
Snowmelt

Snowmelt is often accelerated near arctic and subarctic settlements (Drake 1981, Outcalt et al. 1975). Similar conditions were observed repeatedly near Resolute. To compare the melting of snowpacks within and outside the settlement, the melt energy Q_M for two sites were calculated, using

$$Q_M = Q^* + Q_H + Q_{LE} + Q_R \quad (4)$$

where Q_H is sensible heat flux, Q_{LE} is latent heat flux and Q_R is rain-on-snow melt energy and was equal to zero for the study period since no rainfall occurred.

Data for the computation were acquired for the period June 2 to June 10 1981 at both



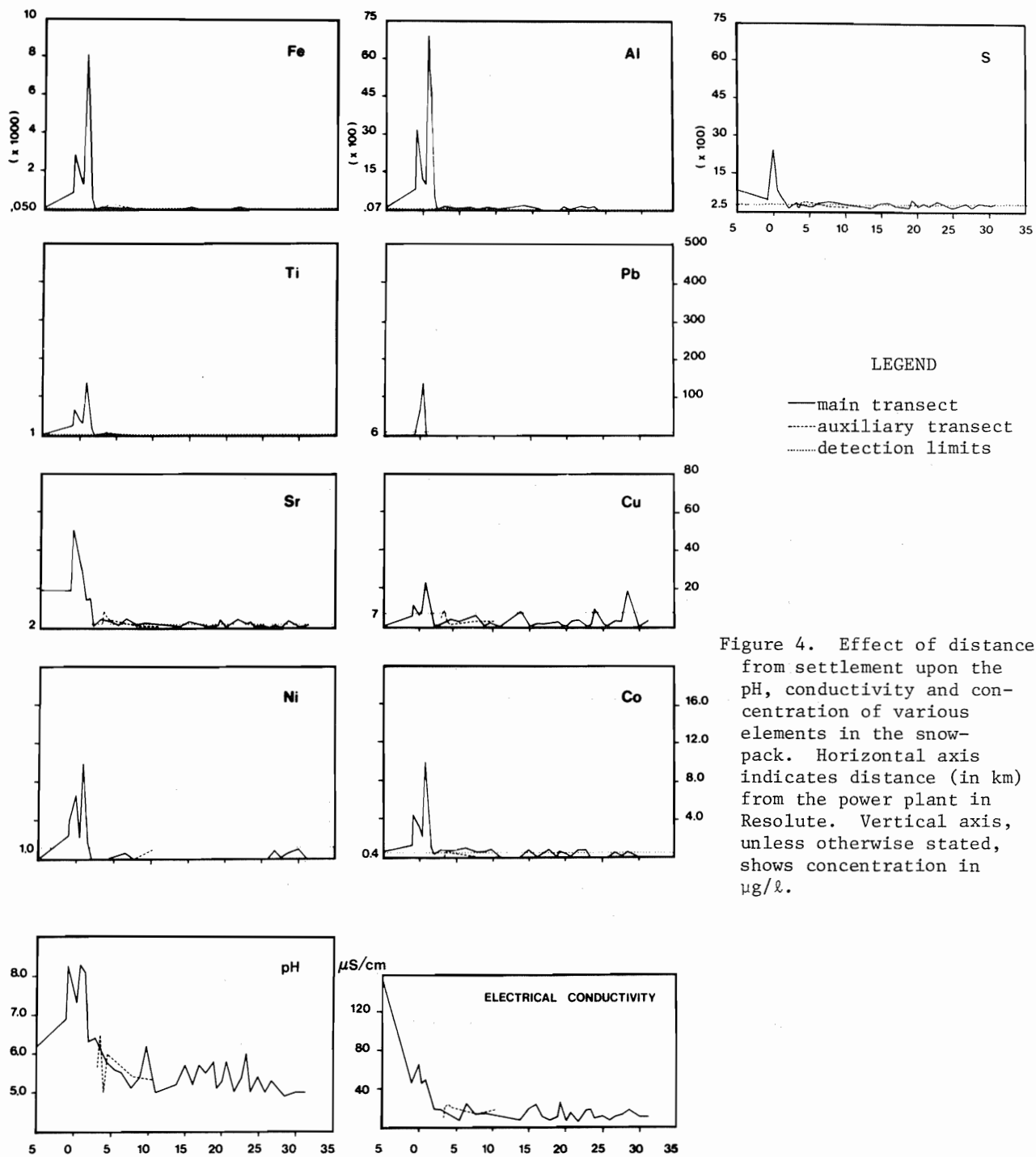


Figure 4. Effect of distance from settlement upon the pH, conductivity and concentration of various elements in the snow-pack. Horizontal axis indicates distance (in km) from the power plant in Resolute. Vertical axis, unless otherwise stated, shows concentration in $\mu\text{g}/\text{l}$.

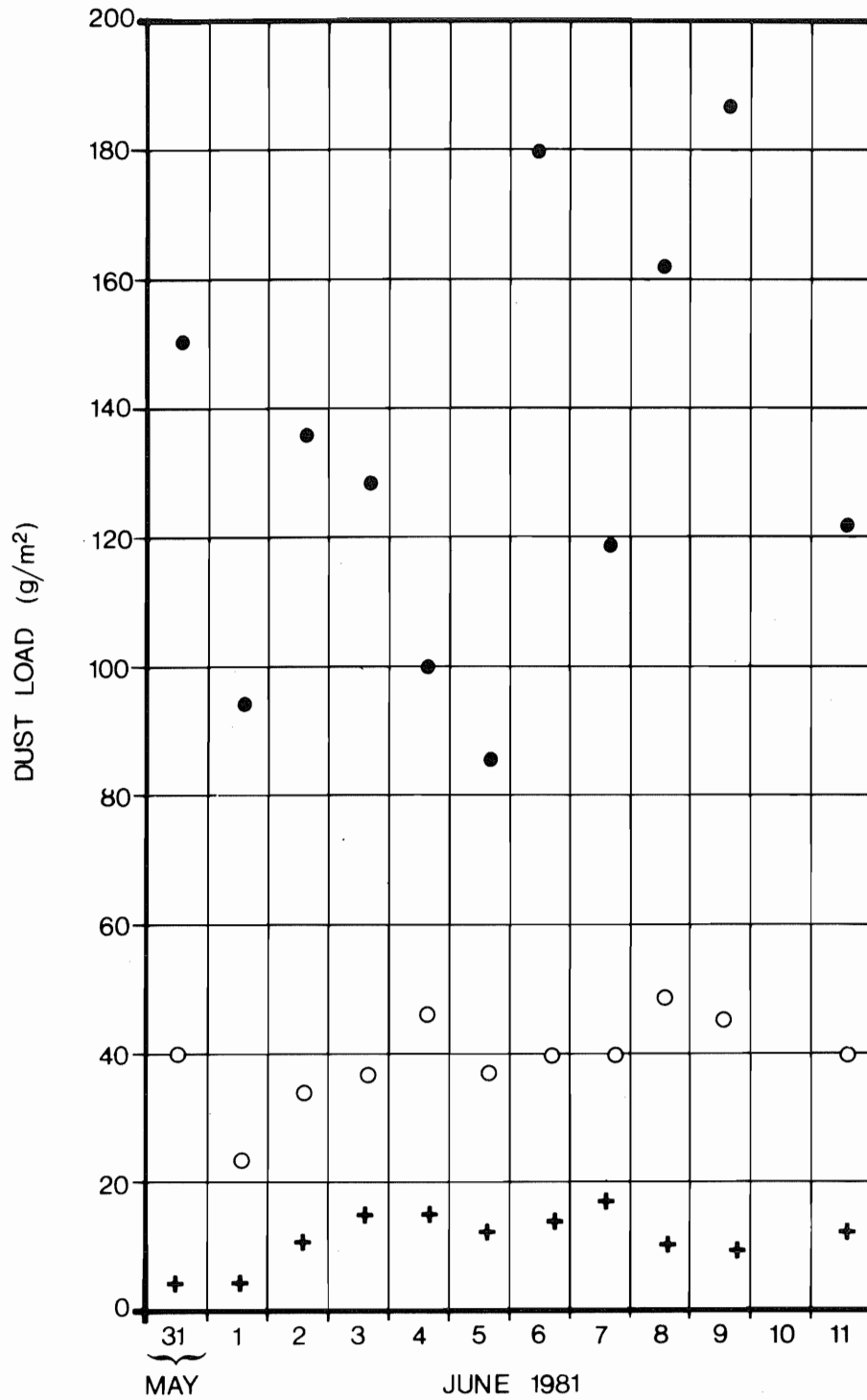


Figure 5. Changes in snow surface dust load at three experimental plots, airstrip site.

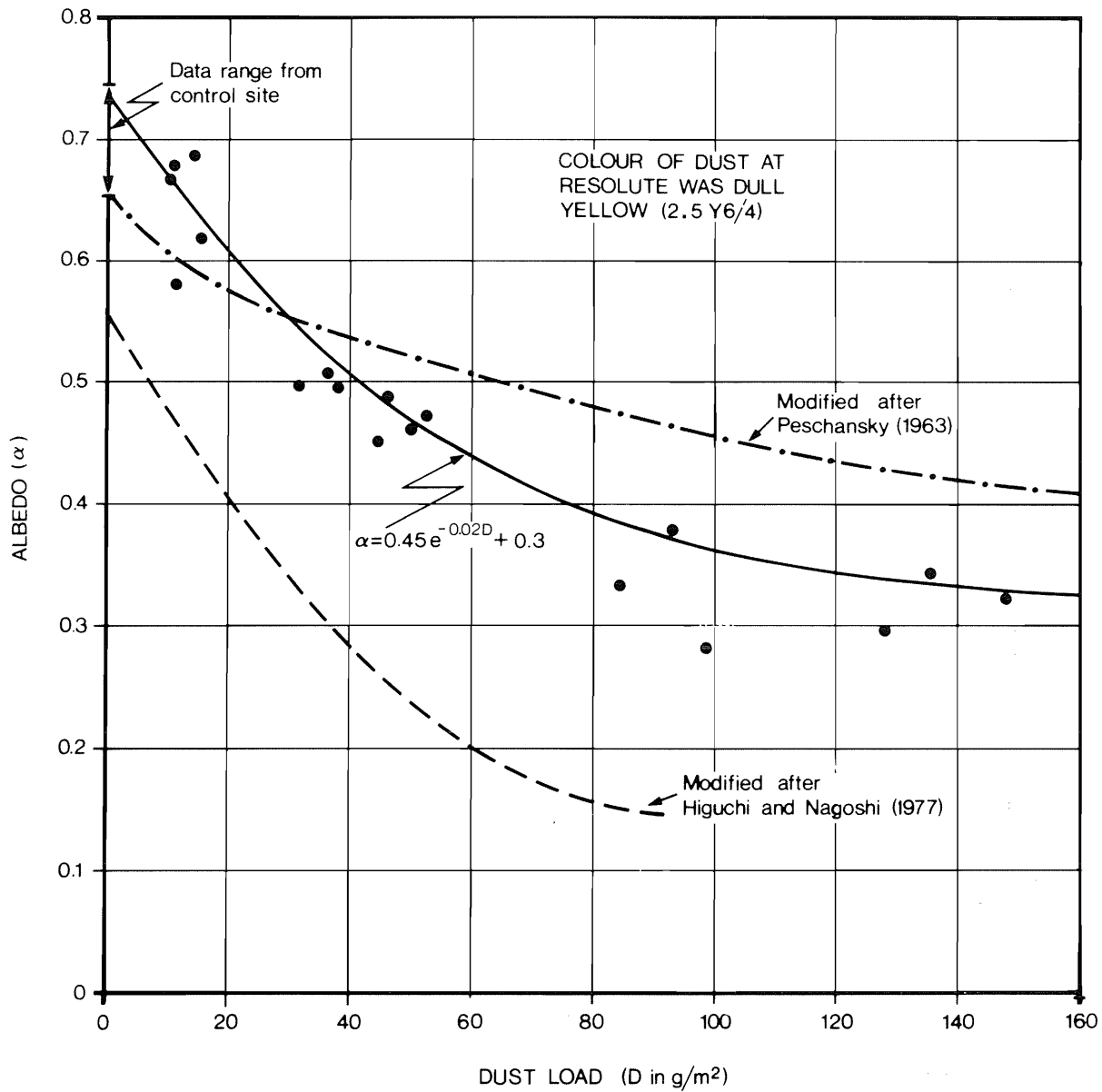


Figure 6. Relationship between midday snow albedo and snow surface dust load. Also included are the relationships observed for a perennial snow patch (Higuchi and Nagoshi) and for dust-covered sea ice (Peschansky).

sites. The calculation of Q_H and Q_{LE} followed the bulk transfer approach (Price and Dunne 1976) which was proven to be suitable for determining arctic snowmelt (Heron and Woo 1978).

Results demonstrate that snowmelt began on June 2 at the airstrip site but melt at the McMaster met. site was delayed for six days (Fig. 7). A breakdown of the melt energy into components given in equation 4 shows that a difference in radiation balance was mainly responsible for the contrast in melt. This indicates the dominant role of albedo, hence the dust content, in influencing differential melting within and outside the arctic settlement. The sensible heat flux also showed a difference reflecting the contrast in temperatures advected over the two sites. The airstrip site, being closer to the centre of town, was usually 0.5°C warmer. At both sites, the latent heat flux was negative and indicates that sublimation occurred. As the melt season progressed, sublimation declined, and the net radiation and the sensible heat were almost entirely used towards snowmelt.

CONCLUSION

Human settlements in the arctic strongly influence the snow hydrology at a local level. An arctic communication centre such as Resolute handles the air traffic for the Arctic Islands and, as such, has developed a settlement that includes an airport, a network of roads, a power-generating plant and a cluster of centrally-heated houses. The many human activities result in an emission of pollutants and an accumulation of dust on the arctic snowpack.

The presence of buildings and other structures also affects the pattern of snow accumulation and adds unevenness to the snow distribution. This, together with snow removal operations, produces areas with shallower patches which disappear quickly once snowmelt begins. The exposed ground is a source of dust to the snowpack nearby, hence decreasing the snow albedo and accelerating the melt. The snowmelt energy balance was compared with that of a site away from the community. The radiation component was mainly responsible for the difference in the energy balance at the two sites. The computed snowmelt based on energy balance considerations agreed with the observation that near Resolute, snowmelt was advanced by about one week.

Field observation and the examination of snow quality and dust load along transects showed that the anthropogenic effects diminished rapidly away from the settlement. Thus, given the present areal extent of most arctic communities and the current level of economic activities, the effect on snow hydrology remains spatially limited.

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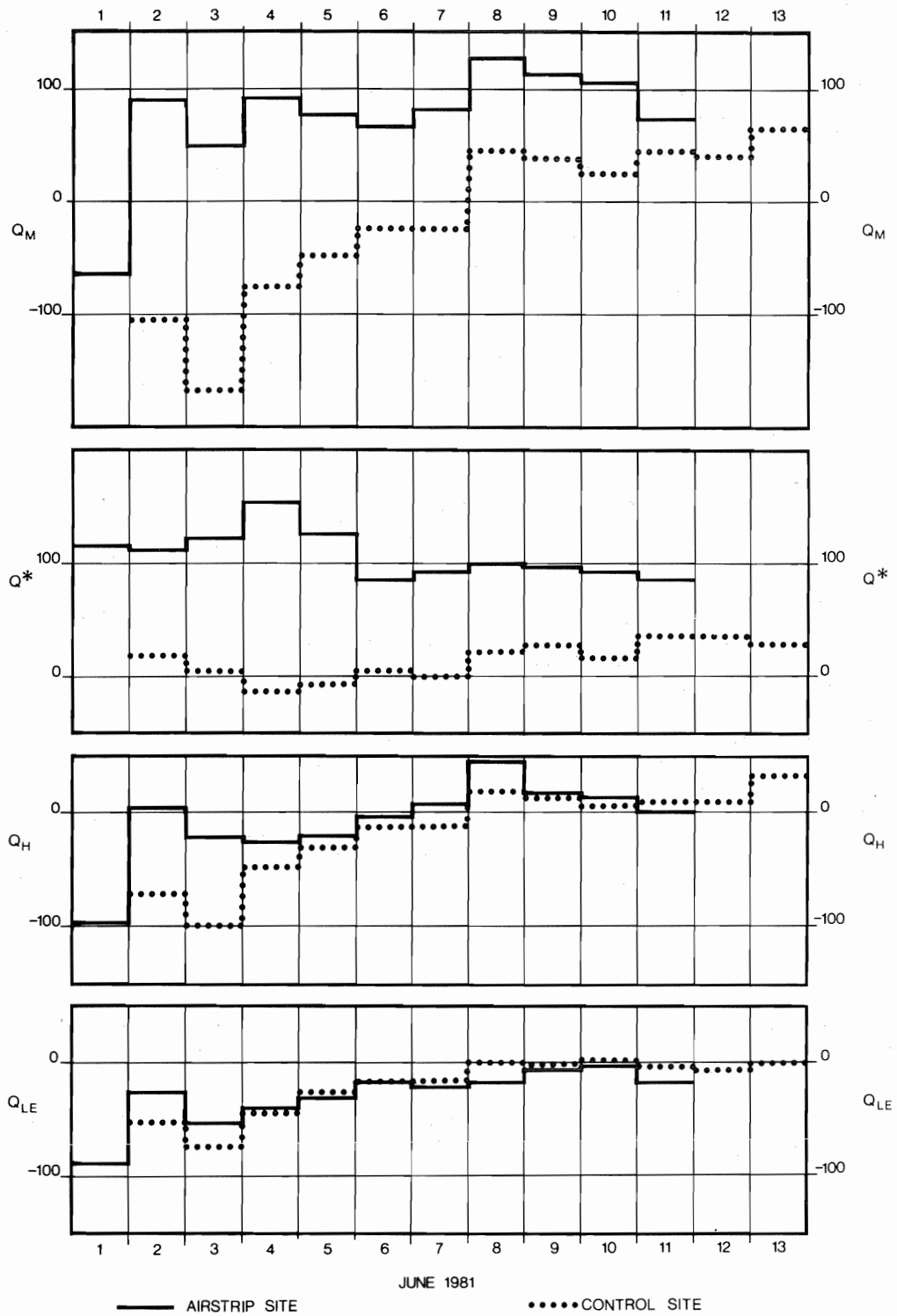


Figure 7. Comparison of daily energy fluxes at the airstrip site and at McMaster met. site during the study period. Fluxes in W/m².

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