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Passive Microwave Applications to Snowpack Monitoring Using Satellite Data

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ABSTRACT

Nimbus-5 Electrically Scanned Microwave Radiometer (ESMR) data were analyzed for the fall of 1975 and winter and summer of 1976 over the Arctic Coastal Plain of Alaska to determine the applicability of those data to snowpack monitoring. It was found that when the snow depth remained constant at 12.7 cm, the brightness temperatures (T_B) varied with air temperature. During April and May the production of ice lenses and layers within the snow, and possibly wet ground beneath the snow contribute to the T_B variations also. Comparison of March T_B values of three areas with the same (12.7 cm) snow depth showed that air temperature is the predominant factor controlling the T_B differences among the three areas, but underlying surface conditions and individual snowpack characteristics are also significant factors.

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INTRODUCTION

Numerous studies have been conducted in order to determine the utility of passive microwave data for snowpack monitoring. Ground, aircraft and satellite platforms have been used. Results from these studies indicate that there is a potential for utilizing passive microwave data for determining the position of the snowline, determining the onset of a snowmelt, for estimating the liquid water content of a snowpack and for determining the condition (wet versus frozen) of the ground beneath a snowpack. Study sites have been located in Colorado (Steamboat Springs, Walden and Fraser), Montana, Washington, the Canadian high plains, and for the present study, the Arctic Coastal Plain of Alaska.

In this paper, progress in analysis of microwave snow properties will be discussed, and Nimbus-5 Electrically Scanned Microwave Radiometer (ESMR) satellite data of snow in northern Alaska will be presented. The Arctic Coastal Plain of Alaska was chosen because it is a very flat, relatively homogeneous area and published data on snow depth and air temperature are available from meteorological stations. Microwave signatures from the Arctic Coastal Plain snow in 1975-1976 are compared with signatures of snow from Montana and the Canadian high plains areas.

MICROWAVE EMISSION FROM SNOW

The emissivity and the temperature of a snowpack affect the measured radiation and result in the observed emission commonly termed the brightness temperature (T_B). Scattering of microwave radiation by individual snow particles causes a lowering of the T_B of the snow. Deeper and denser snow allows greater scattering thus further lowering the T_B. Mie scattering governs the scattering of radiation by snow crystals in a snowpack and is described by Chang et al. (1976).

The condition of the ground beneath the snow will determine the intensity of the radiation incident from below. Dry or frozen ground has a high emissivity (0.9-0.95) whereas wet ground has a much lower emissivity (~0.7) with correspondingly lower brightness temperatures. Knowledge of the condition of the ground underlying the snow is important for the interpretation of observed brightness temperatures and can generally be determined from observations using long microwave wavelengths (Hall et al., 1978).

Many factors influence the microwave emission from the snow itself including snow water equivalent, density, free water within the pack, and grain and crystal sizes. For example, free water within the snow (1–4%) will cause a sharp increase in T_B (Chang and Gloersen, 1975). The T_B sharply increases in response to free water because the water coats the ice crystals in snow thus reducing the radiational scattering which is the major process attributed to lowering the T_B and emission from snow.

Different layers within a snowpack can apparently be analyzed using the multifrequency approach. Penetration through snow can be 10–100 times the wavelength depending upon snow conditions (Chang et al., 1976). Short wavelength radiation is scattered by snow crystals and grains (~1 mm in size) which are comparable in size to the wavelength, as well as by larger scatterers. Longer wavelength radiation is affected by very large crystals, lenses and layers within the snow which result from melting and refreezing of free water which has percolated into the snowpack.

PREVIOUS WORK

During a six week period in 1977 snow varying in depth from 26 cm to 50 cm was studied using truck mounted radiometers observing at three different wavelengths: 0.32 cm (94.0 GHz), 0.81 cm (37.0 GHz) and 2.8 cm (10.69 GHz). Ulaby and Stiles (1979) found that the T_B decreased exponentially with W (water equivalent of snow in cm). They found that the T_B observations reached their lowest levels at W = 30 cm for the 0.81 radiometer and at W = 15 cm for the 0.32 cm radiometer. The 2.8 cm radiometer observations continued to decrease over the range of snow depths observed at that wavelength.

Snow wetness measurements were taken by Stiles and Ulaby (1979) at Steamboat Springs, Colorado during February and March 1977. Ground based radiometer measurements were made at 2.8 cm (10.7 GHz), 0.81 cm (37.0 GHz) and 0.32 cm (94.0 GHz). Snow wetness (m_v), volume percentage of free water in a unit of snow, was measured by the freezing calorimetry technique. It was found that T_B increases with m_v particularly at the 0.81 cm wavelength. The 0.81 cm T_B values increased 110°K while the 2.8 cm radiometer increased only 10°K with the diurnal increase in m_v (Stiles and Ulaby, 1979).

Meier (1972) analyzed data from a 1968 NASA Convair 990 aircraft flight over Mount Rainier, Washington using a 1.55 cm wavelength (19.35 GHz) aircraft model ESMR. He was able to map the snowline based upon the 270°K T_B values. The 270°K boundary compared well with the snowline derived from aerial photography. The 245°K T_B boundary was found to correspond with the transition to the cold, dry snow of the summit plateau of Mount Rainier.

In the winter of 1976 and 1977 aircraft measurements of snow in Colorado were obtained using the Multifrequency Microwave Radiometer (MFMR) on-board the NASA P-3 aircraft (Hall et al., 1978). The MFMR consists of four different wavelengths: 0.81 cm (37.0 GHz), 1.4 cm (22.2 GHz), 1.7 cm (18.0 GHz) and 21.0 cm (1.4 GHz) and was pointing at an angle of 48° forward of the aircraft. Results showed that a decrease in T_B accompanied increasing snow depth and this was best exemplified at the 0.81 cm wavelength as seen in Figure 1. Results from that study also showed an increase in T_B accompanied a small (1–4%) amount of liquid water in the snow.

Both Nimbus-5 and Nimbus-6 ESMR satellite data were used to analyze dry snow over large areas in the United States and Canada. Rango et al. (1979) studied the Canadian high plains area using both 1.55 cm (19.35 GHz) data from the Nimbus-5 ESMR, and 0.81 cm (37.0 GHz) horizontally and vertically polarized data from the Nimbus-6 ESMR. The instantaneous field of view of these instruments from the satellite is about 25 km (at nadir); therefore, only large, homogeneous areas can be studied using these satellite data. Inhomogeneity of the surface underlying the snow can cause differences in T_B values, so a uniform prairie area was selected for the study. Correlations between T_B and snow depth were found to be significant for Nimbus-6 horizontally and vertically polarized data ($R^2 = 0.86$ and $R^2 = 0.71$ respectively) and for the Nimbus-5 data ($R^2 = 0.76$).

NIMBUS-5 ESMR RESULTS FOR THE ARCTIC COASTAL PLAIN OF ALASKA

The Arctic Coastal Plain of Alaska extends from the foothills of the Brooks Range northward to the Arctic Ocean as shown in Figure 2. Snowcover on the North Slope is present 9 months of the year and may attain a maximum depth of 30–40 cm during the spring. The snowpack generally has a dry, high density, wind-packed surface layer which is underlain by a coarse, low density depth hoar layer (Benson et al., 1975). Typically, the snow is shallow enough that it rapidly transmits surface temperature changes through the snowpack according to Benson et al. (1975).

In order to study the relationship between ESMR observations and environmental and snowpack conditions, meteorological data were obtained from stations at Barrow, Barter Island and Galbraith, Alaska for September 1975 through August 1976 (NOAA, 1975 and 1976). Examples of

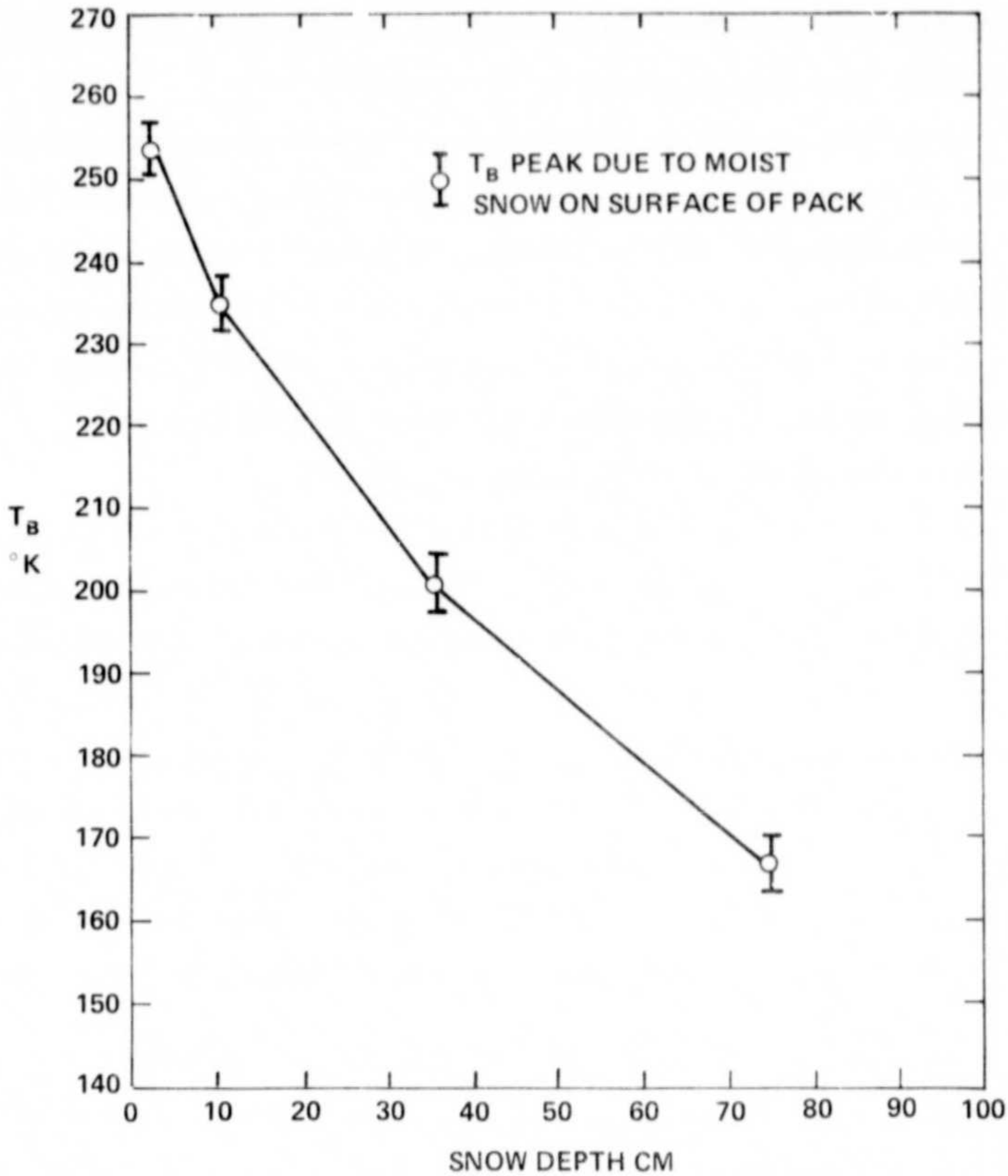

Figure 1. Horizontally Polarized Microwave T_B (0.81 cm) Responses to Snow Depths at Steamboat Springs and Walden, Colorado, 1976 and 1977 (After Hall et al., 1978)

these data showed that only small variations in snow depth existed among the three stations, therefore snow depth and brightness temperature data were averaged for the entire coastal plain area to facilitate comparison of monthly brightness temperatures with the physical temperature of the snow, as inferred from air temperature. Table 1 shows snow depths on the dates of the satellite overpasses which were used to derive the T_B averages.

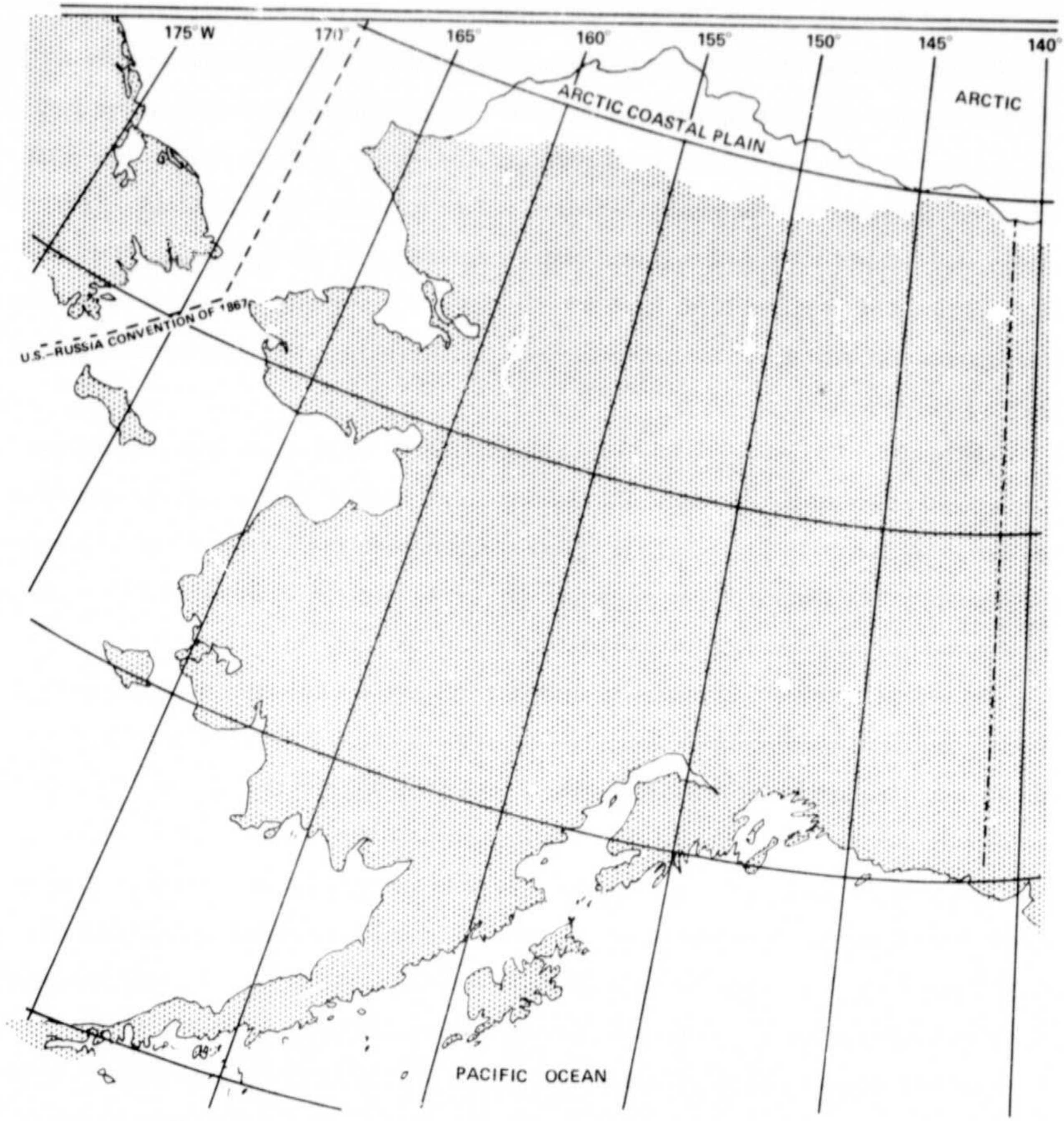

Figure 2. Location Map Showing the Arctic Coastal Plain of Alaska

Table 1
Average Snow on the Ground in cm for the Arctic Coastal Plain of Alaska on the Dates of the Satellite Overpasses

Date	9-25-75	10-17-75	11-18-75	12-20-75	1-16-76	2-19-76	3-18-76	4-19-76	5-21-76	6-22-76	7-20-76	8-23-76
Cm Snow on Ground	2.5	8.5	11.9	12.7	12.7	12.7	13.6	12.7	7.6	T	0	0

Figure 3 shows the variations in brightness temperature derived from Nimbus-5 data for each month from September 1975 to August 1976 along with corresponding average daily air temperatures. The average daily air temperature on the day of each satellite overpass and the average daily temperatures of the four days previous to the overpass were averaged to obtain a temperature value which was representative of the physical temperature of the snowpack. Nimbus-5 ESMR data of Alaska were obtained on a regular basis thus making it possible to obtain a T_B value for at least one day each month of the year in 1976. Nimbus-6 data of Alaska were not used because of the irregular temporal coverage, even though the horizontally polarized data would have been preferable based on previous studies (Rango et al., 1979).

The Nimbus-5 1.55 cm T_B was found to be highest (258°K) in July when the air temperature was higher than any other of the time periods studied as seen in Figure 3. During the transition from summer to fall (August to September), the T_B decreases in response to a combination of the lower air temperature and the addition of snow on the ground. The T_B continues to drop along with average air temperature throughout the fall and winter to its lowest value (220°K) in February.

The average snow depth remained very nearly the same between December and April while the T_B decreased. The ground remained frozen throughout the winter, so it seems safe to conclude that the T_B drop was primarily due to a change in the physical temperature of the snowpack. However, between the months of November and March even though the T_B pattern generally followed the air temperature pattern, the offset between the air temperature and the T_B steadily increased as seen in Figure 3. By April, the spread increased from 15 to 25°K; this increase cannot be explained by air temperature alone. Lowering of the T_B by the end of April with respect to the air temperature, may be due to the production of ice lenses and layers which tend to scatter the microwave radiation and lower the brightness temperature of the snowpack. Wet ground later in the season beneath the snowpack would also lower the T_B. Some snowmelt may occur one month prior to the snowpack becoming isothermal causing lenses and layers to form (Benson et al., 1975).

In support of some of the conclusions concerning snowpack physical temperature, differences in the microwave T_B between the coastal and inland areas of the North Slope were evident during data analysis and can be attributed to variations in air temperature between the coastal and inland areas. During the months of June through October (summer and fall) the 1.55 cm T_B averaged 15° - 59°K higher at the foothills than at the coast due to the effect of continentality allowing the more

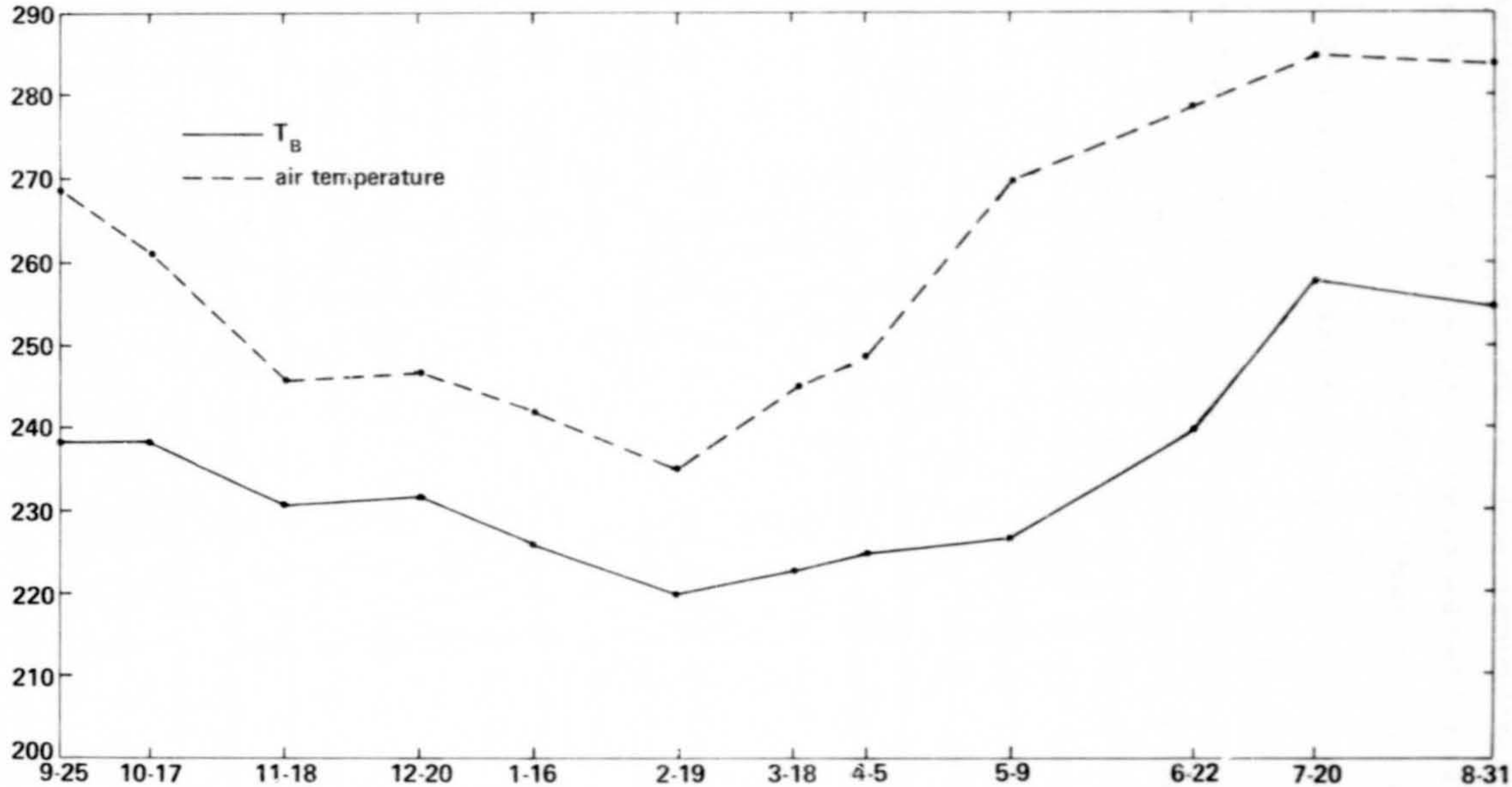

Figure 3. Nimbus-5 T_B Averages and Air Temperatures for the Arctic Coastal Plain

inland areas to heat up more than the coastal areas. During most of the winter months the T_B difference between the coastal and inland areas were negligible; the sea ice on the coast causes a continental type climate at the coast which is similar to the inland climate.

COMPARISON OF THE ARCTIC COASTAL PLAIN AND OTHER AREAS USING NIMBUS-5 SATELLITE DATA

The microwave T_B as determined from Nimbus-5 horizontally polarized data for the snowpack over the North Slope of Alaska on March 18, 1976, was compared to the T_B of the snowpack over the high plains of southern Saskatchewan and Alberta and the high plains of North Dakota and eastern Montana on March 14, 1976. As already noted, the data for these two areas were obtained from a study conducted by Rango et al. (1979).

The North Slope of Alaska is a relatively smooth plain with elevations below 350 m (1150 feet) and is underlain by continuous permafrost and covered by tundra vegetation. The high plains of Canada and the high plains of North Dakota and Montana are composed of rolling plains and low hills with elevations of between 610 - 1525 m (2000 and 5000 feet). Both of these areas are covered by prairie grasses.

On March 18, 1976, the average snow depth of the North Slope area was determined to be 12.7 cm (5.0 inches) and the corresponding T_B was calculated to be 223°K. The average air temperature, T_{air}, was -28°C (245°K). On March 14, 1976 the average snow depth for the high plains of southern Saskatchewan and Alberta was 12.7 cm (5.0 inches) as it was on the Arctic Coastal Plain of Alaska, but the T_B for the area in Canada was 232°K. A substantial fraction of the higher T_B of the Canadian area relative to the Arctic Coastal Plain can be attributed to the higher air temperature, -11°C (262°K) for the Canadian area. For the high plains of North Dakota and eastern Montana the average snow depth was also 12.7 cm (5 inches) and the average T_B was 238°K. The average air temperature was -7°C (266°K). Table 2 presents the March air temperature T_{air}, and brightness temperatures from the Nimbus-5 ESMR data for the three study areas.

Again the differences in physical temperature of the snow (as inferred from air temperature) among the three study areas largely explain the differences in the microwave brightness temperatures because the snow depth is the same in the three areas during the time period studied. However, differences in the density of the snowpacks and the crystal or grain size of the snow particles as well as the underlying surface in each study area also contribute to differences in the microwave response.

Table 2
Brightness Temperatures (T_B) and Air Temperatures (T_{air}) in °K for the Three Study Areas on the Dates of the Nimbus-5 Overpass

	T_B	T_{air}	Date
Alaskan Coastal Plain	223	245	3/18/76
Canadian High Plains	232	262	3/14/76
North Dakota and Montana Plains	238	266	3/14/76

CONCLUSION

It has been demonstrated that even when the snow depth remains constant, the 1.55 cm T_B varies in shallow snow. This was found to be the case on the Arctic Coastal Plain of Alaska between the months of December and April 1976 when the average snow depth was 12.7 cm (5.0 inches) and the T_B offset was 15°K. The variation in T_B was found to be clearly related to physical temperature of the snow (as inferred by air temperature), and also related to changes in snowpack and subsurface conditions between the months of March and May. Additionally, with a constant snow depth (12.7 cm) in three separate areas: the Arctic Coastal Plain of Alaska, the Canadian high plains and the plains of North Dakota and Montana, air temperature differences among the three areas were found to be clearly related to the T_B differences among the three snowpacks. However, the magnitude of the T_B and T_{air} differences indicates that other factors such as internal snowpack differences and variations in the underlying surface of each area are also significant and affect the 1.55 cm brightness temperature.

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