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## SNOWPACK MONITORING IN NORTH AMERICA AND EURASIA USING PASSIVE MICROWAVE SATELLITE DATA

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USING PASSIVE MICROWAVE SATELLITE DATA**

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**ABSTRACT**

Areas of the Canadian high plains, the Montana and North Dakota high plains and the steppes of central Russia have been studied in an effort to determine the utility of spaceborne microwave radiometers for monitoring snow depths in different geographic areas. Significant regression relationships between snow depth and microwave brightness temperatures were developed for each of these homogeneous areas. In each of the study areas investigated in this paper, Nimbus-6 (0.81 cm) ESMR data produced higher correlations than Nimbus-5 (1.55 cm) ESMR data in relating microwave brightness temperature to snow depth. It is difficult to extrapolate relationships between microwave brightness temperature and snow depth from one area to another because different geographic areas are likely to have different snowpack conditions.

## SNOWPACK MONITORING IN NORTH AMERICA AND EURASIA USING PASSIVE MICROWAVE SATELLITE DATA

### INTRODUCTION

Several 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, the snow depth, the onset of snowmelt, the liquid water content of a snowpack, and the condition (wet, dry or frozen) of the underlying soil beneath a snowpack. In this paper, areas of the Canadian high plains, the Montana and North Dakota high plains, and the steppes of central Russia have been studied in an effort to determine the utility of spaceborne microwave radiometers for monitoring snow depths in different geographic areas.

Analysis of microwave snow properties will be discussed, and Nimbus-5 and -6 Electrically Scanning Microwave Radiometer (ESMR) satellite data of snow in the above listed study areas will be presented. Each of the study areas is relatively flat and homogeneous and published data on snow depth and air temperature are available from snow courses and meteorological stations.

### MICROWAVE EMISSION FROM SNOW

The emissivity and the temperature of a snowpack affect the measured radiation which is 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 (0.90-0.95) whereas wet ground has a much lower emissivity ( $\sim 0.70$ ) 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, liquid water within the pack, and grain and crystal sizes. For example, liquid 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 liquid 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 liquid water which has percolated down into the snowpack (Shiue et al., 1978).

## PREVIOUS WORK

During a six week period at Steamboat Springs, Colorado 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 (1980) 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 cm 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 also taken at Steamboat Springs during February and March 1977 (Stiles and Ulaby 1980). Snow wetness ( $m_v$ ), i.e., volume percentage of liquid water in a unit of snow, was measured by the freezing calorimetry technique. It was found that  $T_B$

increased 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, 1980).

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-mounted 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.

Both Nimbus-5 and Nimbus-6 ESMR satellite data have been used to analyze dry snow over large areas in the United States and Canada. Rango et al., (1979) studied the Canadian high plains area (Fig. 1) 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 (Nimbus-5 ESMR records only horizontally polarized data). 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 relatively uniform prairie area was selected for the study.

Correlations between  $T_B$  and snow depth were found to be significant (at the 0.001 level) for the Nimbus-5 data where  $R^2 = 0.76$  (Fig. 2), and for the Nimbus-6 vertically polarized data where  $R^2 = 0.86$  (Fig. 3). Analysis of the horizontally polarized Nimbus-6 data produced results essentially similar to the vertically polarized data. Multiple regression approaches using brightness temperatures from both Nimbus-5 and 6 as predictor variables provided no marked improvement in the relationships.

## STUDY AREAS

It is the purpose of this paper to expand on the work discussed above by Rango et al., (1979). Two additional geographical areas were selected to study the relationship between snow depth and microwave  $T_B$ . These areas are the steppes of central Russia (Figure 4) and the high plains of Montana and North Dakota (Figure 5). The vegetation, topography, climate, and latitude in both of these areas, and the high plains of Canada as well, are comparable and each area covers about  $2.33 \times 10^5 \text{ km}^2$  ( $9.00 \times 10^4 \text{ mi}^2$ ). The vegetation is predominately a variety of grasses and the topography although generally flat, is broken by low hills. Each of these areas experiences very cold winters with snow covering the ground during much of December, January, February, and March. Elevations in the Russian test site for the most part are less than 305 m (1000 ft.), whereas elevations in the Canadian and U.S. test sites range between 610-1524 m (2000-5000 ft.). Nimbus-5 and 6 data and snow depth values from a network of meteorological stations were obtained on 20 January 1976, for the central Russian steppes. For the Canadian and U.S. test sites Nimbus-5 and 6 data were obtained on 14 and 15 March 1976, respectively. (Only vertically polarized Nimbus-6 data were used in this paper.) Snow depths in Canada were reported at snow course sites and meteorological stations on 15 March 1976, but in the U.S., due to a limited number of snow courses on the high plains of Montana and North Dakota, snow depths were usually recorded at city airports, also on 15 March 1976. Air temperatures in each of the study areas, before and during the satellite passes, were below  $0^\circ\text{C}$  ( $32^\circ\text{F}$ ) with little chance of significant melting and, as a result, dry snow conditions were assumed. Temperatures were somewhat colder in central Russia, and somewhat warmer in Montana-North Dakota, than in the Canadian study area. Nimbus-5 data over the Canadian and U.S. study areas were obtained during nighttime passes. Nimbus-5 data over central Russia and Nimbus-6 data for each of the three study areas were obtained during daytime passes. For each of the three study areas snow depth values were used to draw isonivals which were then averaged over  $1^\circ$  latitude by  $1^\circ$  longitude grid blocks. Brightness temperatures were also averaged over the same grid blocks so that snow depth and  $T_B$  could be compared and used in regression analysis.

## RESULTS AND DISCUSSION

Snow depth and  $T_B$  data from each of the  $1^\circ$  by  $1^\circ$  grid blocks were plotted for all three areas combined. Figures 6 and 7 show the Nimbus-5 and -6  $T_B$  versus snow depth scatter plots and resulting regression relationships, respectively. Both regressions are significant at the 0.005 level with  $R^2$  values of 0.55 for the Nimbus-5 data and 0.51 for the Nimbus-6 data. The fact that these  $R^2$  values are lower than those reported in the previous work by Rango et al. (1979) probably results from combining the various geographical areas with associated differences in snowpack characteristics and underlying soil properties causing a greater scatter in the  $T_B$ s. It should be noted, especially in the Nimbus-6 plot (Figure 7), that the Canadian data seem to be well separated from the Russian and U.S. data. Because the data plots from each of the study areas are not scattered randomly in Figures 6 and 7, further regression runs were performed on each of the data sets as was done originally in the Canadian study.

Figures 8 and 9 respectively present Nimbus-5 and -6  $T_B$ s plotted versus snow depth for the steppes of central Russia. The regression using Nimbus-5 data in Figure 8 has an  $R^2$  value of 0.52 and is significant at the 0.005 level, whereas the Nimbus-6 regression in Figure 9 has an  $R^2$  of 0.60, significant at the 0.001 level. Between Figures 6 and 7 and Figures 8 and 9 very little change in regression fit was noted except for a uniform decrease in the standard errors (SE) in Figures 8 and 9.  $R^2$  values decreased slightly for the Nimbus-5 data and improved somewhat for the Nimbus-6 data. When compared to the earlier Canadian study results, the  $R^2$  values of the Russian data are much lower (Canadian Nimbus-5  $R^2 = 0.76$  versus Russian Nimbus-5  $R^2 = 0.52$ ; Canadian Nimbus-6  $R^2 = 0.86$  vs Russian Nimbus-6  $R^2 = 0.60$ ). The poorer correlations found in the Russian study area are probably largely a result of lower quality ground data used in the analysis. Very little information about snow depth measurement technique, time of observation, and standardization between measuring stations was available for this analysis. In addition, much less was known about study site characteristics than in either the Canadian and U.S. sites, and, as a result, the Russian area could be much less homogeneous than assumed. Snow and climatic conditions before the satellite passes were difficult to quantify so they were assumed to be similar to the other two



data sets. Unusual snowpack metamorphism could be a cause of a difference between the fit of the various data sets.

Nimbus-5 and -6  $T_B$ s versus snow depths on the high plains of Montana and North Dakota are illustrated in Figures 10 and 11. The Nimbus-5 data (Figure 10) has a  $R^2$  of 0.81 and the regression is significant at the 0.001 level. The Nimbus-6 data (Figure 11) has a  $R^2$  of 0.88 and is also significant at the 0.001 level. These correlations are much higher than those found on the central Russian steppes but comparable to those found on the high plains of Canada. This may be attributed to the fact that the  $T_B$  and snow depth data were obtained on the same days for the Canadian and U.S. study areas. In addition, because of their proximity, these two areas are apparently more similar to each other than they are to the steppes of central Russia. There are some slight physical differences between the two areas, such as temperature, precipitation, vegetation and soil, that might cause the regression equation form (slope and intercept) to differ considerably. As a result it would be difficult to extrapolate results from any one study area to each of the other two.

When each study area is considered separately, the Nimbus-6  $R^2$  values are consistently higher than the Nimbus-5  $R^2$  values (when the data are lumped together, however, the Nimbus-5  $R^2$  is slightly greater than the Nimbus-6  $R^2$ ). To a large degree this general pattern can be associated with the fact that the shorter wavelength of 0.81 cm for Nimbus-6 does not sense emission from as deep in the snowpack as the somewhat longer wavelength of 1.55 cm for Nimbus-5. As a result the Nimbus-6 data are less sensitive than the Nimbus-5 data to the variable nature of the underlying ground conditions. The  $T_B$  signal recorded by Nimbus-6 would then be expected to be more highly correlated with snow depth, and the Nimbus-5  $T_B$  signal to be degraded by variable emission from subsurface characteristics. The combination of three separate data sets into one apparently tends to nullify this general trend.

## CONCLUSIONS

1. Variations in snow accumulation and depletion at specific locations cause variations in passive microwave brightness temperatures observed from Nimbus satellites. Qualitative monitoring of snowpack build-up and disappearance during the winter appears feasible in a given area.
2. In relatively homogeneous areas of the Canadian high plains, the Montana and North Dakota high plains, and the steppes of central Russia, significant regression relationships between snow depth (criterion variable) and microwave brightness temperature (predictor variable) were developed. The estimation of snow depth under dry snow conditions in these study areas is thus a possibility using microwave data. A greater range of  $T_B$  and snow depth need to be acquired for estimation purposes.
3. In each of these three study areas investigated in this paper, Nimbus-6 (0.81 cm) ESMR data produced higher correlations than Nimbus-5 (1.55 cm) ESMR data in relating microwave brightness temperature to snow depth. The shorter wavelength 0.81 cm data appear to be more sensitive to the structure and condition of the snow than does the longer wavelength 1.55 cm data which is additionally affected by underlying soil conditions.
4. Because different geographic areas are likely to have different snowpack conditions, ground cover, underlying soil conditions and surface temperatures, it is difficult to extrapolate relationships between microwave brightness temperature and snow depth from one area to another. Specific relationships must be derived for individual areas and should be useful in improving assessment of snowpack conditions over large areas.

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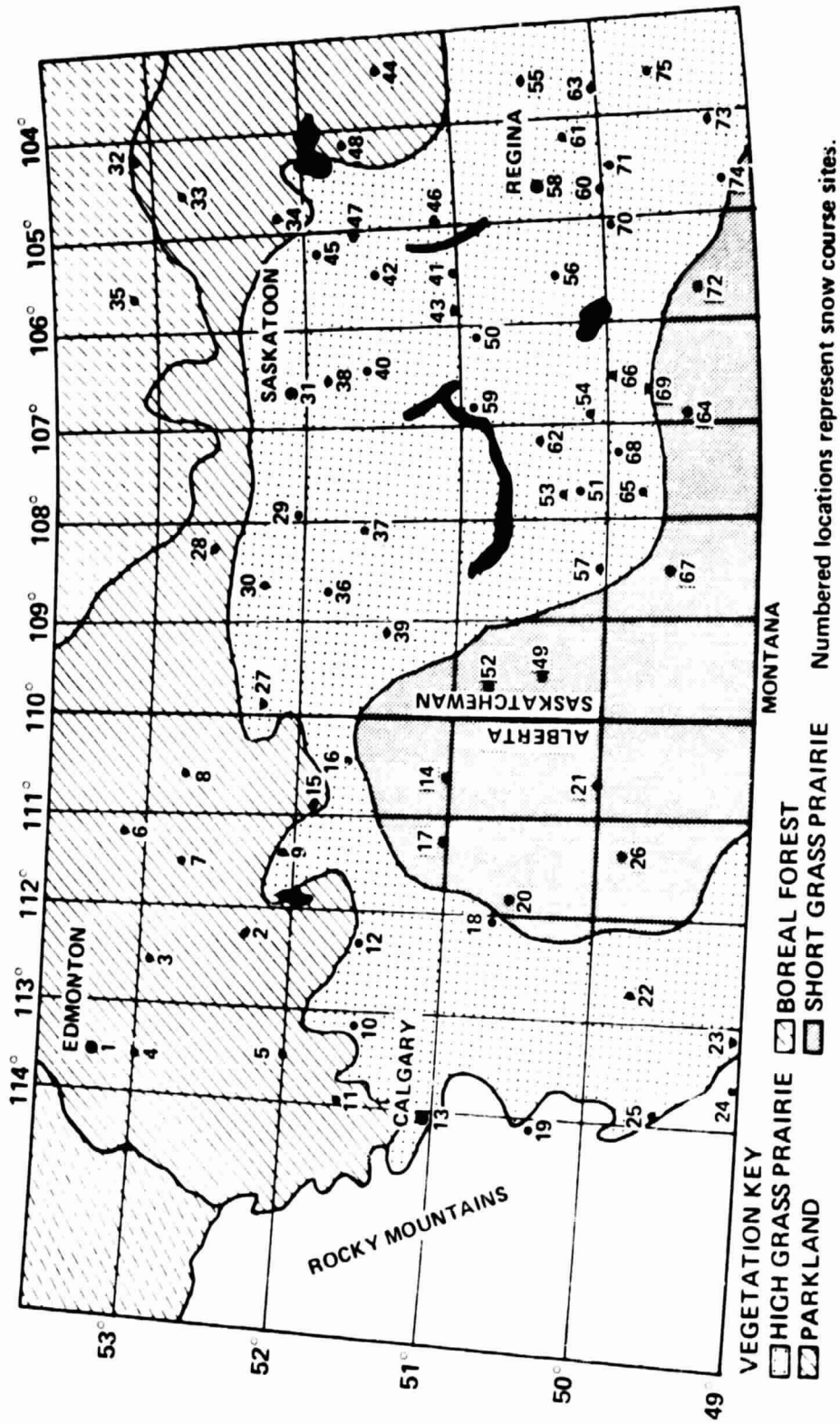


Figure 1. The Canadian high plains snow/microwave study area (Rango et al., 1979).

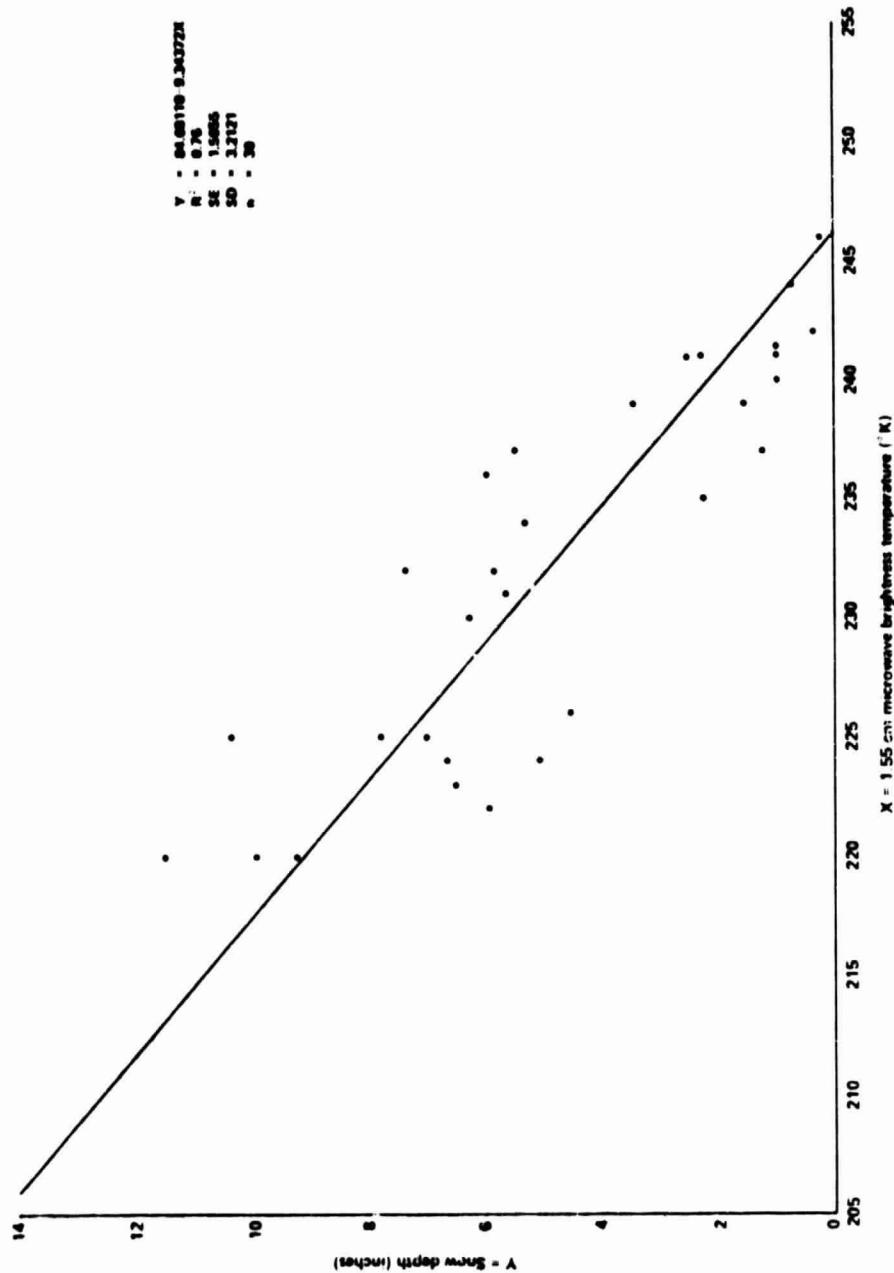


Figure 2. Nimbus-5 microwave brightness temperature versus snow depth on the Canadian high plains. Nimbus-5 data from night-time pass 14 March 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 summarized over same grid; data included from short and high grass prairie areas only. (Rango et al., 1970)

$R^2$  = coefficient of determination      SD = standard deviation  
 SE = standard error                      n = number of grid observations

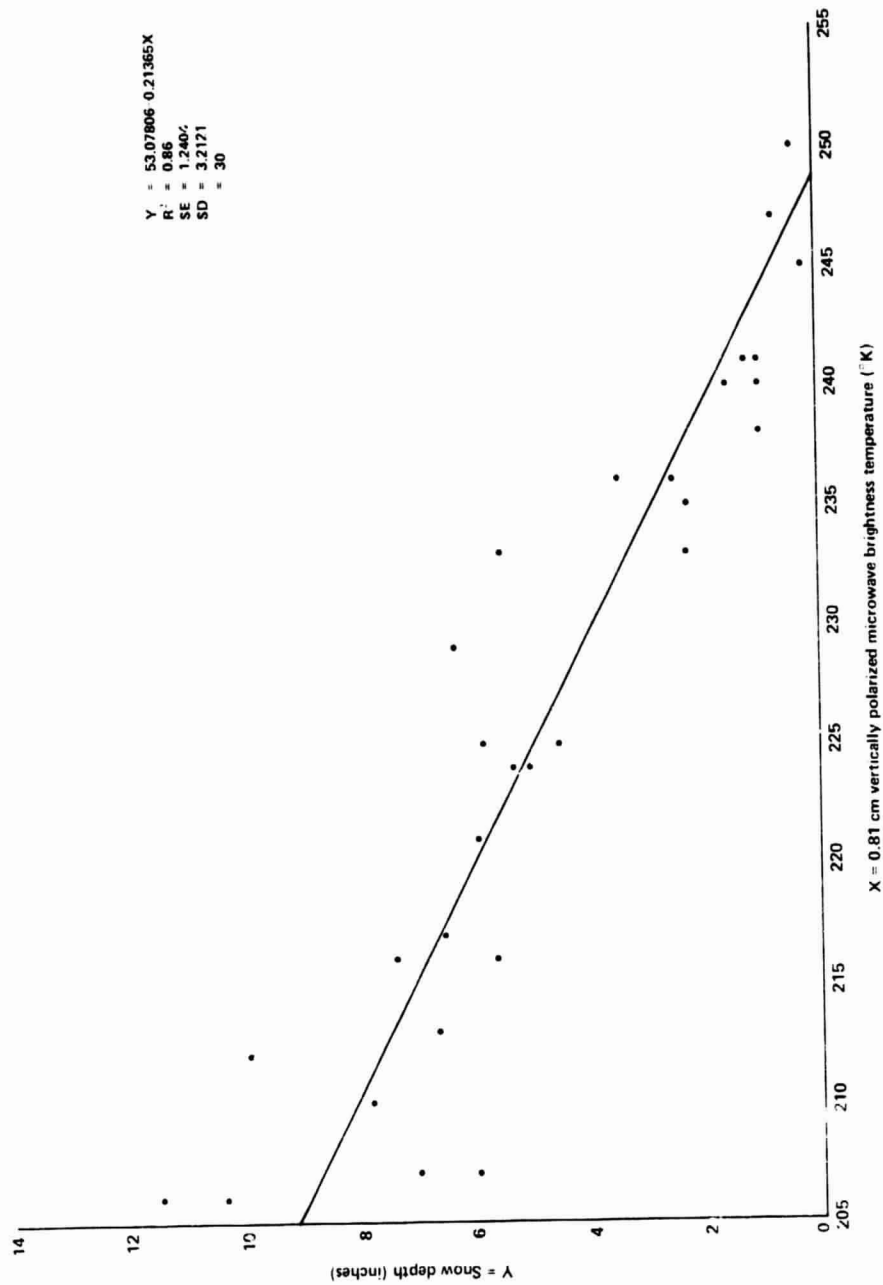


Figure 3. Nimbus-6 vertically polarized microwave brightness temperature versus snow depth on the Canadian high plains. Nimbus-6 data from daytime pass 15 March 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 summarized over same grid; data included from short and high grass prairie areas only. (Rango et al., 1979)

$R^2$  = coefficient of correlation      SD = standard deviation  
 SE = standard error                      n = number of grid observations

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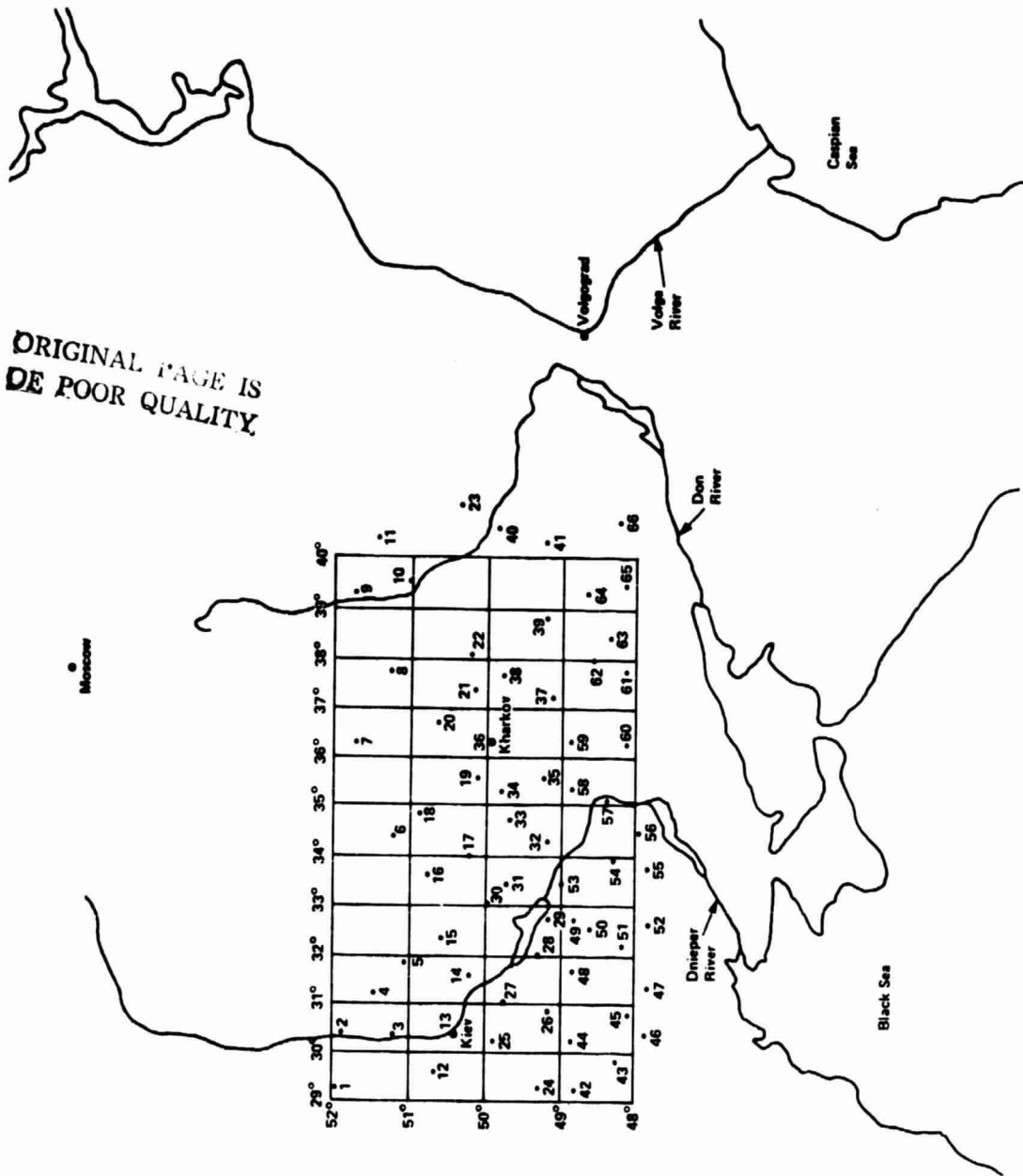


Figure 4. Central Russia snow/microwave study area. Numbered locations represent meteorological stations reporting snow depth.



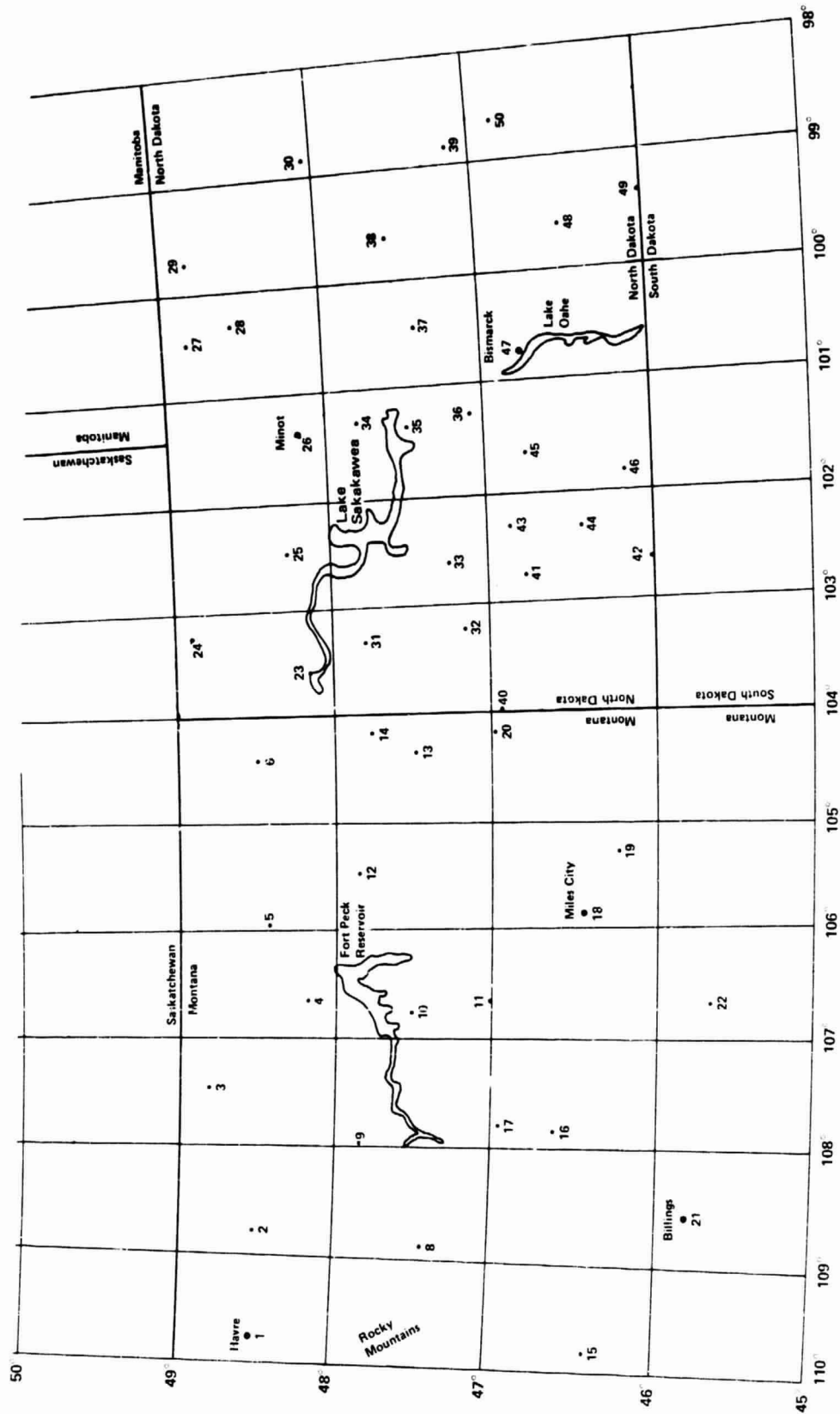


Figure 5. The North Dakota-Montana snow/microwave study area. Numbered locations represent city airports reporting snow depth.

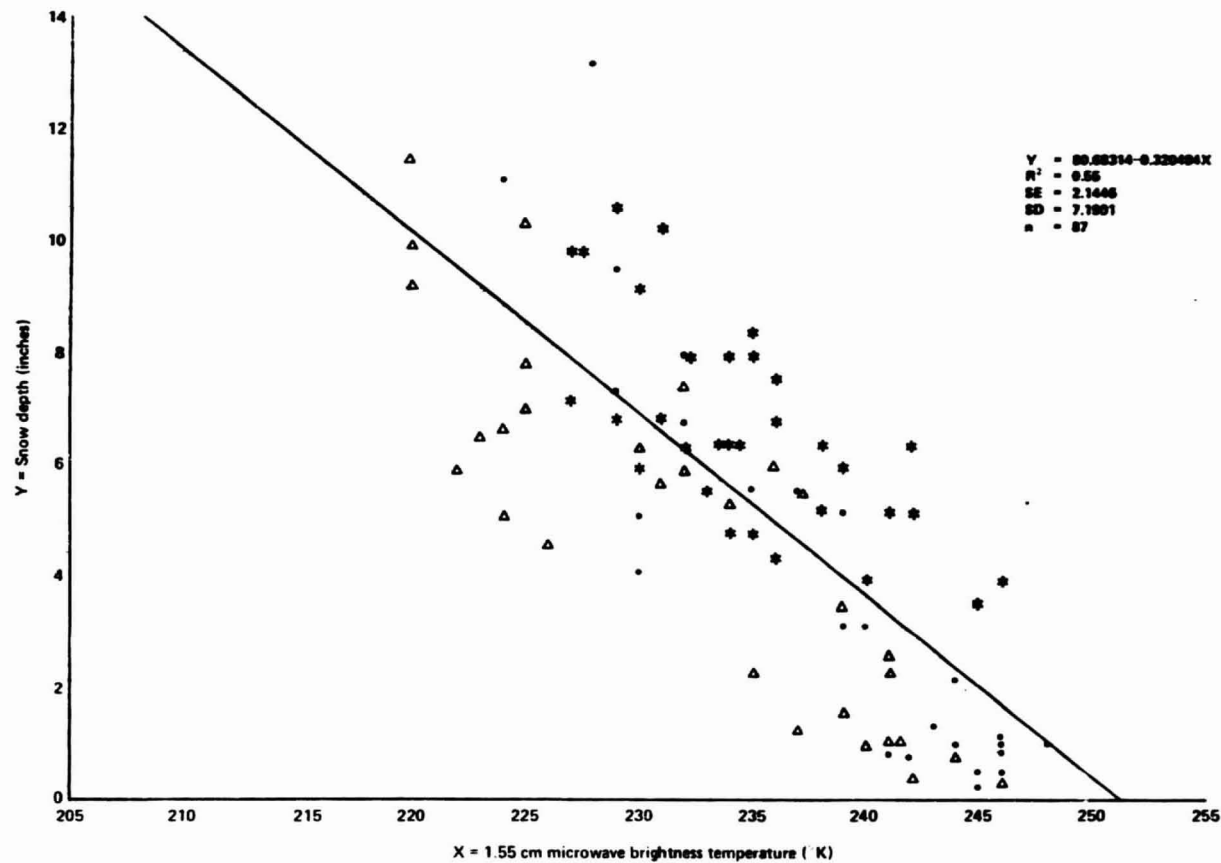


Figure 6. Nimbus-5 microwave brightness temperatures for the Canadian, U.S., and Russian study areas versus snow depth. Nimbus-5 data from nighttime pass on 14 March 1976 and daytime pass on 20 January 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 and 20 January 1976 summarized over same grid.

$R^2$  = coefficient of determination  
 SE = standard error  
 SD = standard deviation  
 n = number of grid observations

$\Delta$  data from Canadian high plains  
 \* data from central Russian steppes  
 • data from Montana and North Dakota.

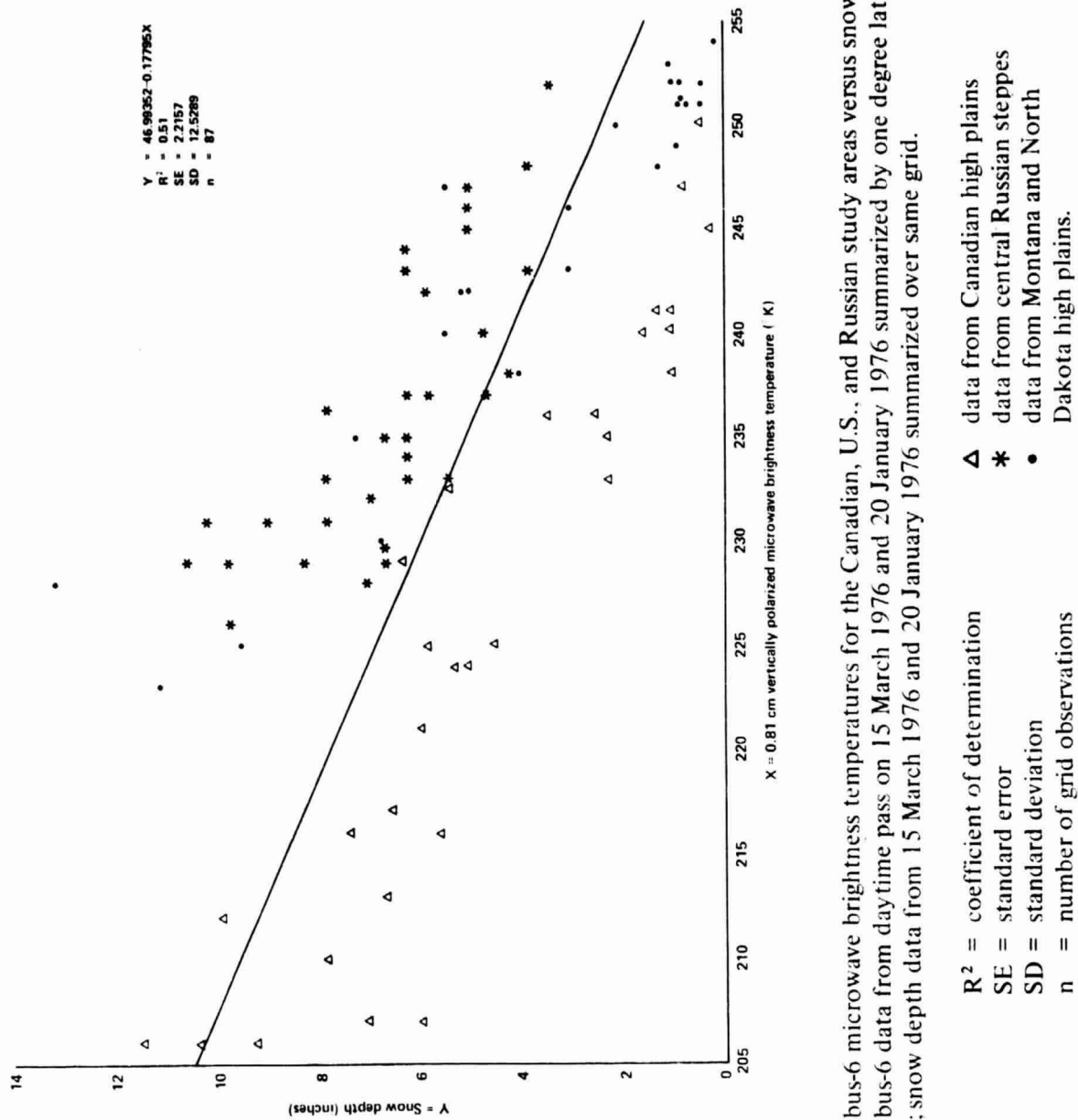


Figure 7. Nimbus-6 microwave brightness temperatures for the Canadian, U.S., and Russian study areas versus snow depth. Nimbus-6 data from daytime pass on 15 March 1976 and 20 January 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 and 20 January 1976 summarized over same grid.

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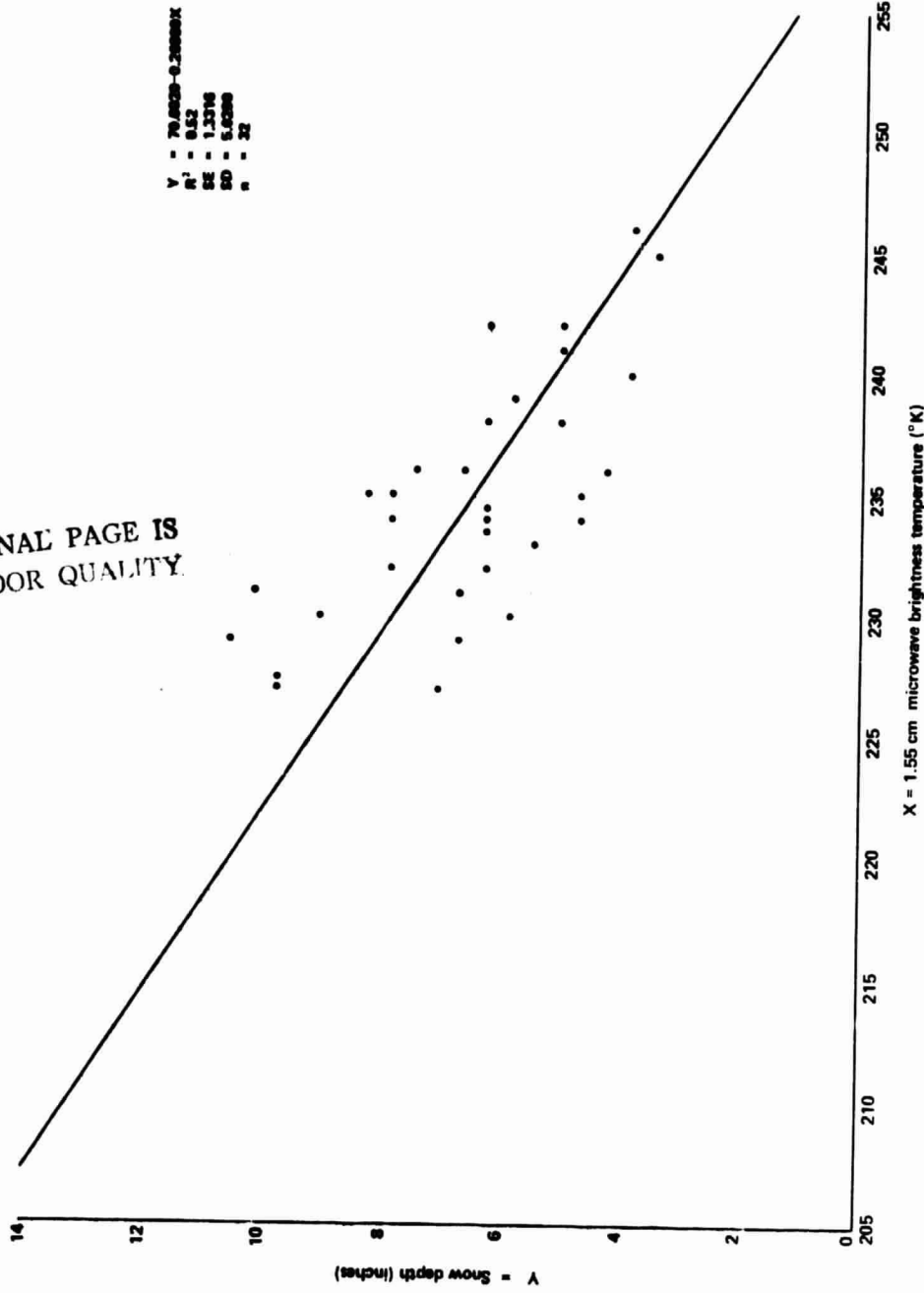


Figure 8. Nimbus-5 microwave brightness temperature versus snow depth on the Russian steppe. Nimbus-5 data from daytime pass 20 January 1976 summarized by one degree latitude-longitude grid; snow depth data from 20 January 1976 summarized over same grid.

$R^2$  = coefficient of determination  
 SE = standard error

SD = standard deviation  
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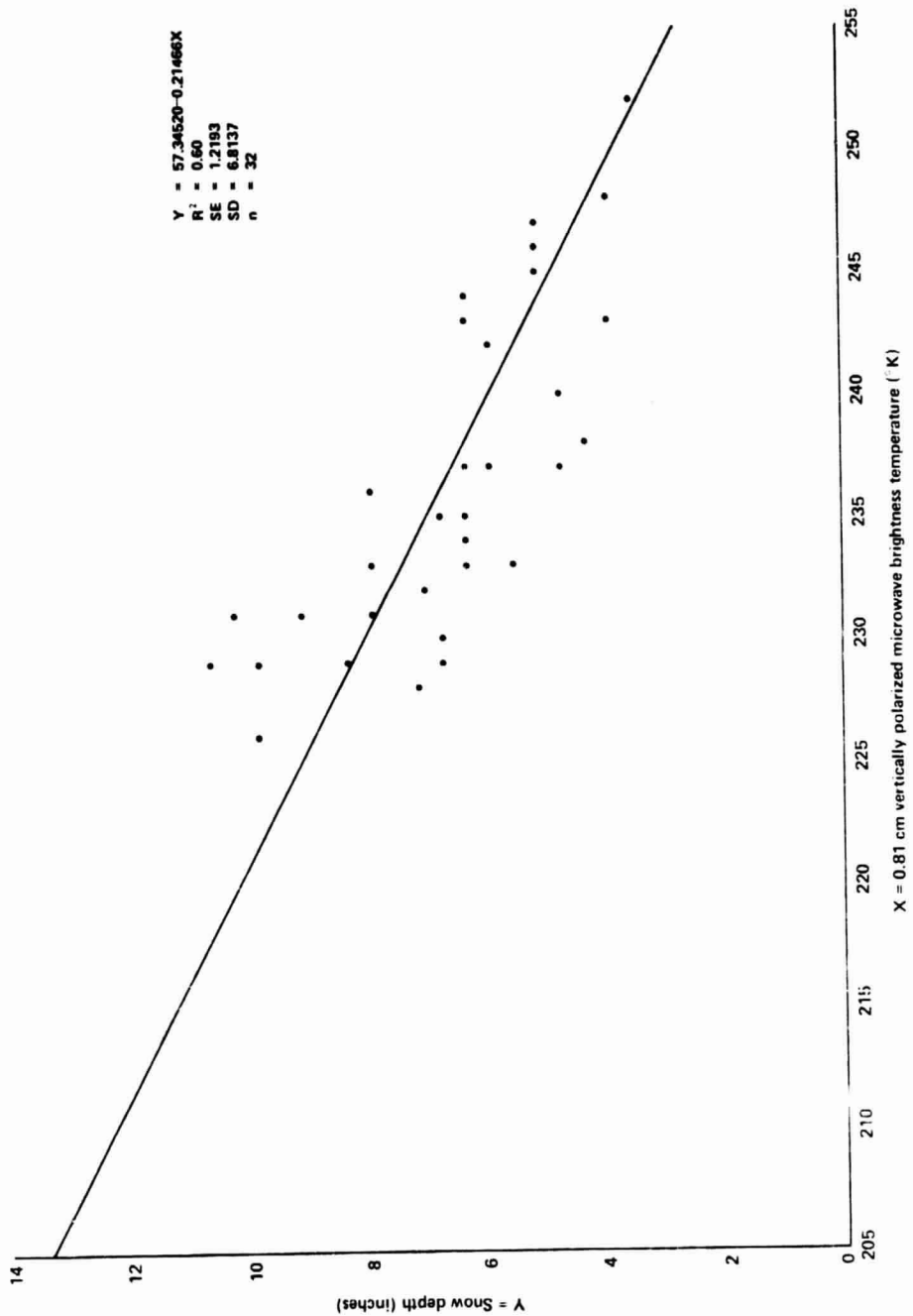


Figure 9. Nimbus-6 vertically polarized microwave brightness temperature versus snow depth on the Russian steppe. Nimbus-6 data from daytime pass 20 January 1976 summarized by one degree latitude-longitude grid; snow depth data from 20 January 1976 summarized over same grid.

$R^2$  = coefficient of determination  
 $SE$  = standard error  
 $SD$  = standard deviation  
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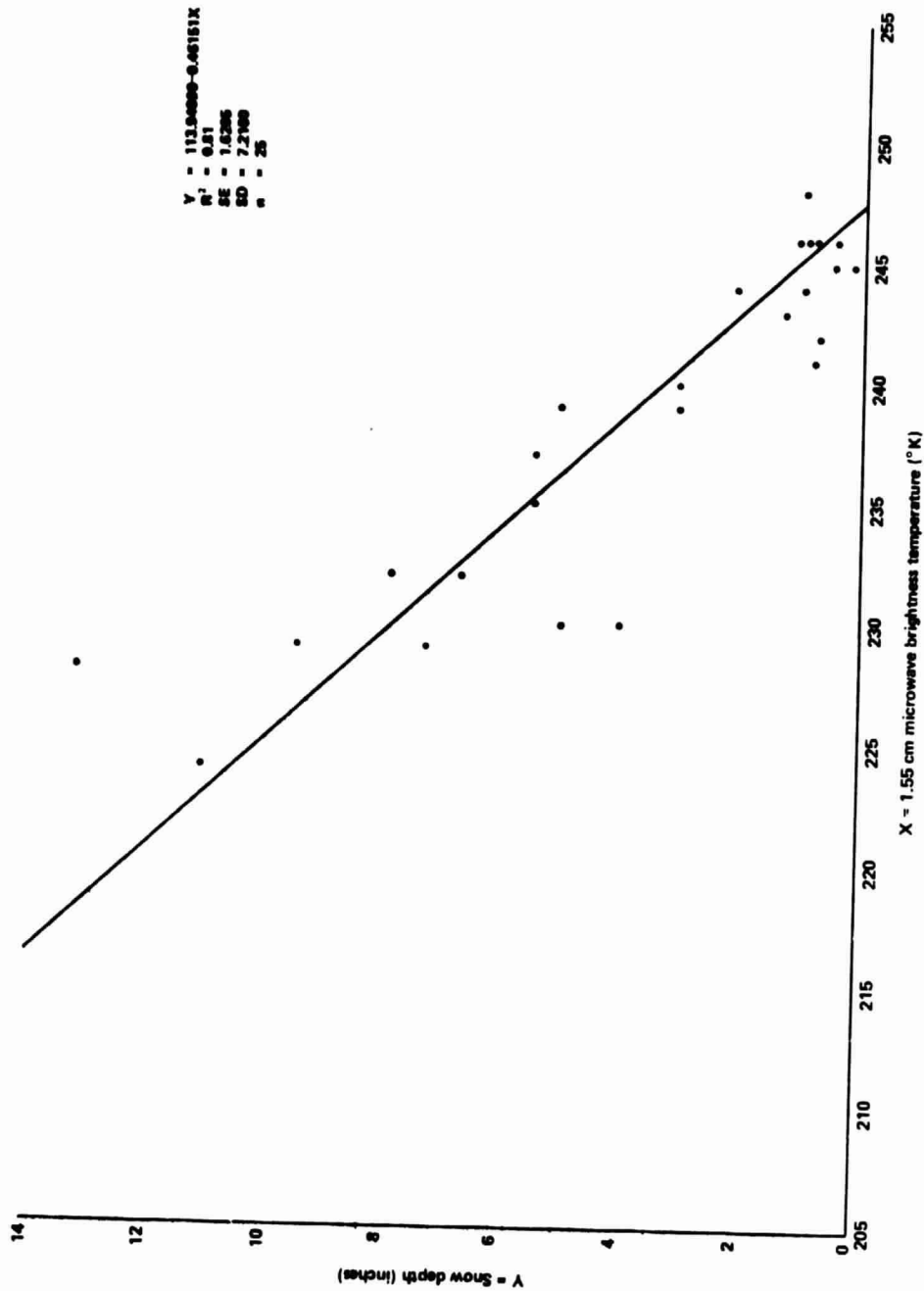


Figure 10. Nimbus-5 microwave brightness temperature versus snow depth on the high plains of Montana and North Dakota. Nimbus-5 data from nighttime pass 14 March 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 summarized over same grid.

R<sup>2</sup> = coefficient of determination  
 SE = standard error

SD = standard deviation  
 n = number of grid observations

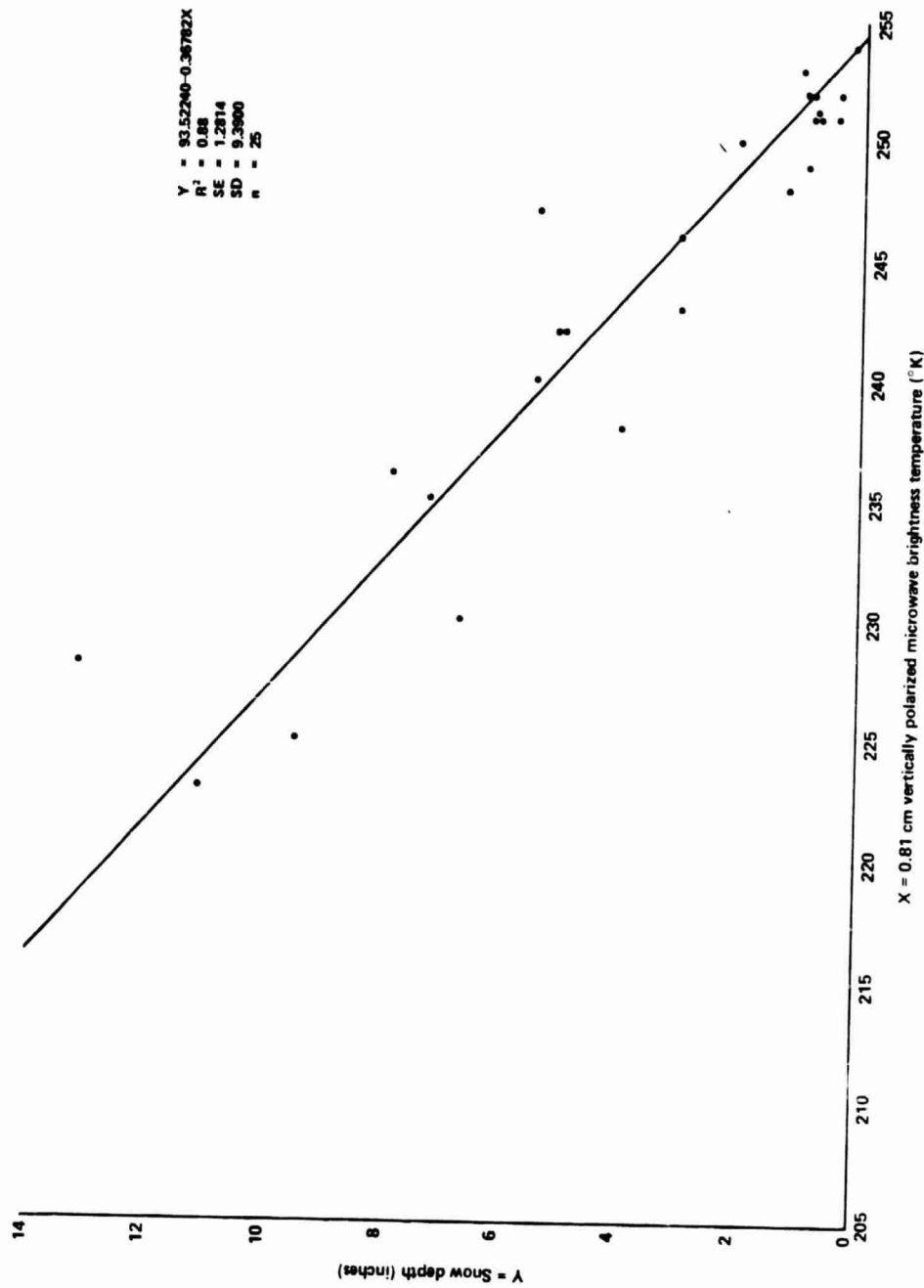


Figure 11. Nimbus-6 vertically polarized microwave brightness temperature versus snow depth on the high plains of Montana and North Dakota. Nimbus-6 data from daytime pass 15 March 1976 summarized by one degree latitude-longitude grid; snow depth data from 15 March 1976 summarized over same grid.

$R^2$  = coefficient of determination  
 SE = standard error  
 SD = standard deviation  
 n = number of grid observations

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