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J. L. FOSTER, D. K. HALL, A. T. C. CHANG,
A. RANGO, L. J. ALLISON, AND B. C. DIESEN, III

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National Aeronautics and
Space Administration

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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ABSTRACT

Areas of the steppes of central Russia, the high plains of Montana and North Dakota, and the high plains of Canada have been studied in an effort to determine the relationship between passive microwave satellite brightness temperature, surface air temperature, and snow depth. Significant regression relationships were developed in each of these homogeneous areas. Results show that R^2 values obtained for air temperature versus snow depth and the ratio of microwave brightness temperature and air temperature versus snow depth were not as high as the R^2 values obtained by simply plotting microwave brightness temperature versus snow depth. Multiple regression analysis provided only marginal improvement over the results obtained by using simple linear regression.

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Greenbelt, Maryland

INTRODUCTION

Studies performed by Abrahms and Edgerton (1977), Rango et al. (1979), and Foster et al. (1980) among others have demonstrated that statistically significant regression relationships exist between snow depth and Electrically Scanning Microwave Radiometer (ESMR) satellite data. The strength of the relationship and the form of the regression line results to a large degree from the homogeneity of the area and the structure and condition of the snowpack. The microwave brightness temperature (T_B) is a measure of the emissivity and the physical temperature of the snowpack. Snow particles act as scattering centers for microwave radiation. Computational results indicate that scattering from individual snow particles within a snowpack is the dominant source of upwelling emission in the case of dry snow. Because a deep snowpack obviously has more crystals and/or grains to scatter microwave radiation than a shallow snowpack does, the T_B will be lower (Chang and Gloersen, 1975). Snow particle size and shape, liquid water in the snowpack, snow density, and the condition of the underlying surface also affect the amount of scattering and consequently the emissivity of the snowpack. The physical temperature of the snowpack, especially the upper layers of snow, is primarily a result of the surface air temperature (T_{air}). In this study, snow depth was plotted against the surface air temperature to determine if this approach produced a relationship similar to that which exists between snow depth and microwave brightness temperature. Also, snow depth was plotted against the ratio, T_B/T_{air}, an index of the emissivity, to determine if this would result in a stronger correlation than that obtained by using only T_B or T_{air} versus snow depth. In addition, multiple regression analysis was used to determine the relationship between snow depth and Nimbus (ESMR) T_B and T_{air} to see if any improvement in the coefficient of determination (R^2) resulted from using multiple regression analysis as opposed to simple (single variable) regression analysis.

PREVIOUS WORK

Rango et al. (1979) and Foster et al. (1980) used Nimbus 5 and 6 Electrically Scanning Microwave Radiometer (ESMR) data in an attempt to determine if a correlation exists between snow depth and T_B in homogeneous regions of Canada, the United States, and Russia. They found that the coefficient of determination (R^2) between snow depth and T_B was 0.76 for the horizontally polarized Nimbus 5 (1.55 cm) ESMR data and 0.86 for the vertically polarized Nimbus 6 (0.81 cm) ESMR data for the Canadian high plains study area. The R^2 values for the high plains of Montana and North Dakota were 0.81 for the Nimbus 5 ESMR data and 0.88 for the Nimbus 6 data, and, for the steppes of central Russia, the R^2 values were 0.52 and 0.56 for the Nimbus 5 and 6 ESMR data respectively. In these three homogeneous study areas, the relatively high R^2 values and the statistically significant regression relationships that were developed indicate that passive microwave data are potentially useful for estimating snow depth for dry snow conditions.

Hall et al. (1979) demonstrated that, even when the snow depth remains constant, the Nimbus 5 (1.55 cm) T_B varies in shallow snow. This was the case on the Arctic Coastal Plain of Alaska between the months of December and May 1976 when the average snow depth was 12.7 cm (5.0 inches) and the T_B varied by 15 K. The variation in T_B was clearly related to physical temperature of the snow (as inferred by air temperature), and to changes in snowpack and subsurface conditions between the months of March and May. In addition, 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 in the three areas clearly influenced the T_Bs of 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, also significantly affected the 1.55 cm brightness temperature (Hall et al., 1979).

STUDY AREAS

The study areas and data sources used in this paper are the same as those described by Foster et al. (1980). The study areas are the steppes of central Russia (Figure 1), the high plains of Montana and North Dakota (Figure 2), and the high plains of Canada (Figure 3). The vegetation, topography, climate, and latitude of these areas are comparable, and each area covers about 2.33 x 10^5 km^2 (9.00 x 10^4 mi^2). The predominant vegetation consists of grasses, and the topography, although generally flat, is broken by 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 are, for the most part, less than 305 m (1000 ft), whereas elevations in the Canadian and U. S. test sites range between 610 and 1524 m (2000 and 5000 ft). Snow depth values and surface air temperatures from a network of meteorological stations were obtained on January 20, 1976, for the central Russian steppes. Nimbus 5 and 6 data were also obtained on this day. For the Canadian and U. S. test sites, Nimbus 5 and 6 data were obtained on March 14 and 15, 1976, respectively. (Only vertically polarized Nimbus 6 data were used in this paper.) Snow depths in Canada were recorded at snow course sites and meteorological stations, but in the United States, they were usually recorded at city airports because of the limited number of snow courses on the high plains of Montana and North Dakota.

Air temperatures in Canada and the United States were obtained from airport stations. Air temperatures in each of the study areas, both before and during the satellite passes, were near or below 0°C (32°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 and North Dakota than in the Canadian study area. For better comparison with microwave T_B, T_{air} was converted to degrees Kelvin (K). 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 study areas were obtained during daytime passes. For each of the three study areas, snow depth values were used to draw isonivals and air temperatures were used to draw isotherms, which were then averaged over 1-degree latitude by 1-degree longitude grid blocks. Brightness temperatures were also averaged over the same grid blocks so that snow depth, T_{air}, and T_B could be compared and used in regression analysis.

DISCUSSION AND RESULTS

Snow depth and air temperature data from each of the 1- by 1-degree grid blocks were plotted for the three study areas (Russia, the United States, and Canada). Figures 4, 5, and 6 show the air temperature data versus snow depth scatter plots and resulting regression relationships. All three regressions were significant at the 0.005 level with R^2 values of 0.44, 0.72, and 0.73 for Russia, the United States, and Canada, respectively. In this study, the average daily temperature (T_{ave}) was used as an indicator of air temperature (T_{air}). T_{ave} is obtained by simply dividing the sum of the daily maximum temperature (T_{max}) and the daily minimum temperature (T_{min}) by two. An attempt was made to determine if either T_{max} or T_{min} provided more information than T_{ave} in relating T_{air} to snow depth. However, it was found that, in each study area, T_{ave} produced as good or better correlations than T_{max} or T_{min}. T_{ave} also proved better than T_{max} or T_{min} in relating Nimbus 5 and 6 brightness temperature to T_{air}.

Even though the R^2 values obtained by relating T_{ave} to snow depth are significant for each of the study areas, they are not as high as the R^2 values obtained by relating either Nimbus 5 or Nimbus 6 T_B data to snow depth. The R^2 values between Nimbus 5 T_B and snow depth for Russia, the United States, and Canada were 0.52, 0.81, and 0.76, respectively, and the R^2 values between Nimbus 6 T_B and snow depth for Russia, the United States, and Canada were 0.60, 0.88, and 0.86, respectively (Foster et al., 1980). (See Table 1.)

Snow depth data were also plotted against an index of the emissivity (T_B/T_{air}) by again using the data from each 1- by 1-degree grid for the three study areas. Figures 7 and 8 show the Nimbus 5 and 6 T_B data versus snow depth scatter plots for Russia and the resulting regression relationships. Figures 9 and 10 show the Nimbus 5 and 6 data versus snow depth scatter plots for the United States, and similarly, Figures 11 and 12 show the Nimbus 5 and 6 data versus snow depth scatter plots for Canada. All the regressions were significant at the 0.005 level except for the Nimbus 5 T_B/T_{air} data versus snow depth in Russia, which was significant at the 0.01 level. The R^2 values obtained for each of these plots are not as high as the R^2 values obtained by simply relating T_B to snow depth (Table 1). It also can be seen from Table 1 that, for the Russian and Canadian study areas, T_B/T_{ave} versus snow depth regressions produce results similar to those obtained by regressing T_{ave} versus snow depth (Nimbus 5 values being slightly lower than Nimbus 6 values). However, for the U. S. study area (Montana and North Dakota), the R^2 values obtained between T_B/T_{ave} and snow depth, using both Nimbus 5 and Nimbus 6 data, were higher than the R^2 value between T_{ave} and snow depth.

Multiple regression analysis was used to determine the relationship between T_B and T_{ave} (two predictor variables) and snow depth for both Nimbus 5 and Nimbus 6 data. The results are presented in Table 2. It can be seen that the R^2 values obtained using two predictor variables are only slightly better or the same as the R^2 values obtained by using only Nimbus 5 or Nimbus 6 T_B data versus snow depth (Table 1). Multiple regression analysis was also used to determine the relationship governing three predictor variables (1.55-cm T_B, 0.81-cm T_B, and T_{ave}) and snow depth. These results (Table 2) are the same as those obtained by using only 0.81-cm T_B and T_{ave} versus snow depth. This indicates that the 1.55-cm data contribute virtually nothing to the R^2 values obtained by using 0.81-cm T_B and T_{ave} as the predictor variables. For both the two-variable and the three-variable approaches, multiple regression analysis provided no marked improvement to the results obtained by using simple linear regression analysis. Rango et al. (1979) also arrived at this conclusion when they related 1.55-cm T_B and 0.81-cm T_B to snow depth.

CONCLUSIONS

1. For each of the study areas (Russia, the United States, and Canada), there was a statistically significant relationship between the average daily temperature (T_{ave}) and the snow depth. The R^2 values obtained by plotting the average daily temperature versus snow depth were not as high as the R^2 values obtained by relating either Nimbus 5 or Nimbus 6 brightness temperature (T_B) data versus snow depth.

2. There was a statistically significant relationship between an index of the emissivity (T_B/T_{ave}) and snow depth for each study area. The R^2 values obtained between T_B/T_{ave} and snow depth were again not as high as those obtained by simply plotting T_B versus snow depth. Results obtained by plotting T_B/T_{ave} versus snow depth were basically similar to those obtained by plotting T_{ave} versus snow depth.

3. Multiple regression analysis using 1.55-cm T_B, 0.81-cm T_B, and T_{ave} as predictor variables provided only marginal improvement over the results obtained by using simple linear regression to relate T_B to snow depth.

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Table 1
R^2 values

	Russia	Montana-North Dakota	Canada
1.55-cm T_B vs. snow depth	0.52	0.81	0.76
0.81-cm T_B vs. snow depth	0.60	0.88	0.86
Air Temp (T_{ave}) vs. snow depth	0.44	0.72	0.73
1.55-cm T_B/T_{ave} vs. snow depth	0.37	0.74	0.63
0.81-cm T_B/T_{ave} vs. snow depth	0.56	0.81	0.83

Table 2
R^2 values

	Russia	Montana-North Dakota	Canada
1.55-cm $T_B + T_{ave}$ vs. snow depth	0.52	0.84	0.81
0.81-cm $T_B + T_{ave}$ vs. snow depth	0.60	0.91	0.86
1.55-cm T_B + 0.81-cm $T_B + T_{ave}$ vs. snow depth	0.60	0.91	0.86

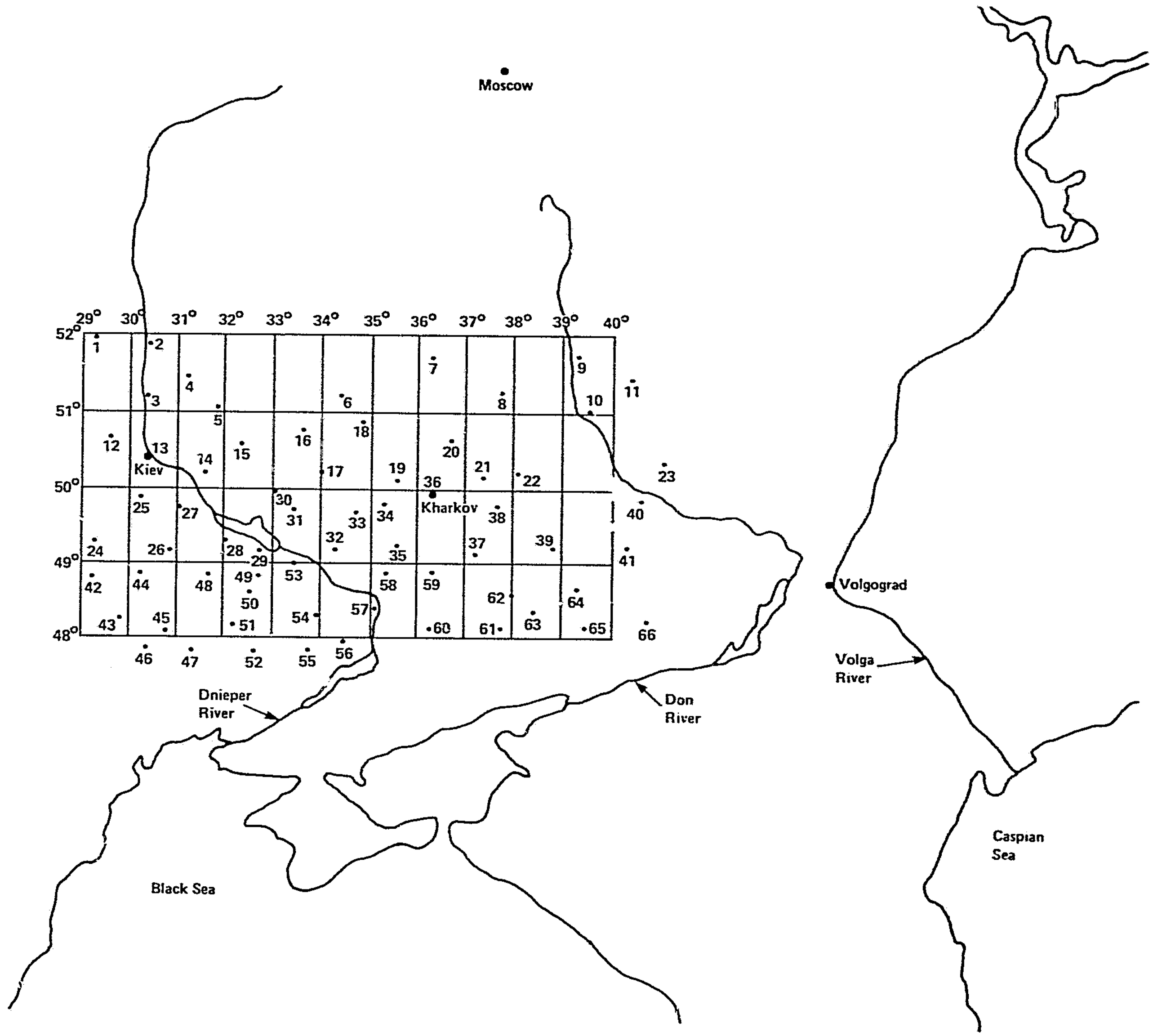

Figure 1. Central Russian steppes snow/microwave study area. Numbered locations represent meteological stations (Foster et al., 1980).

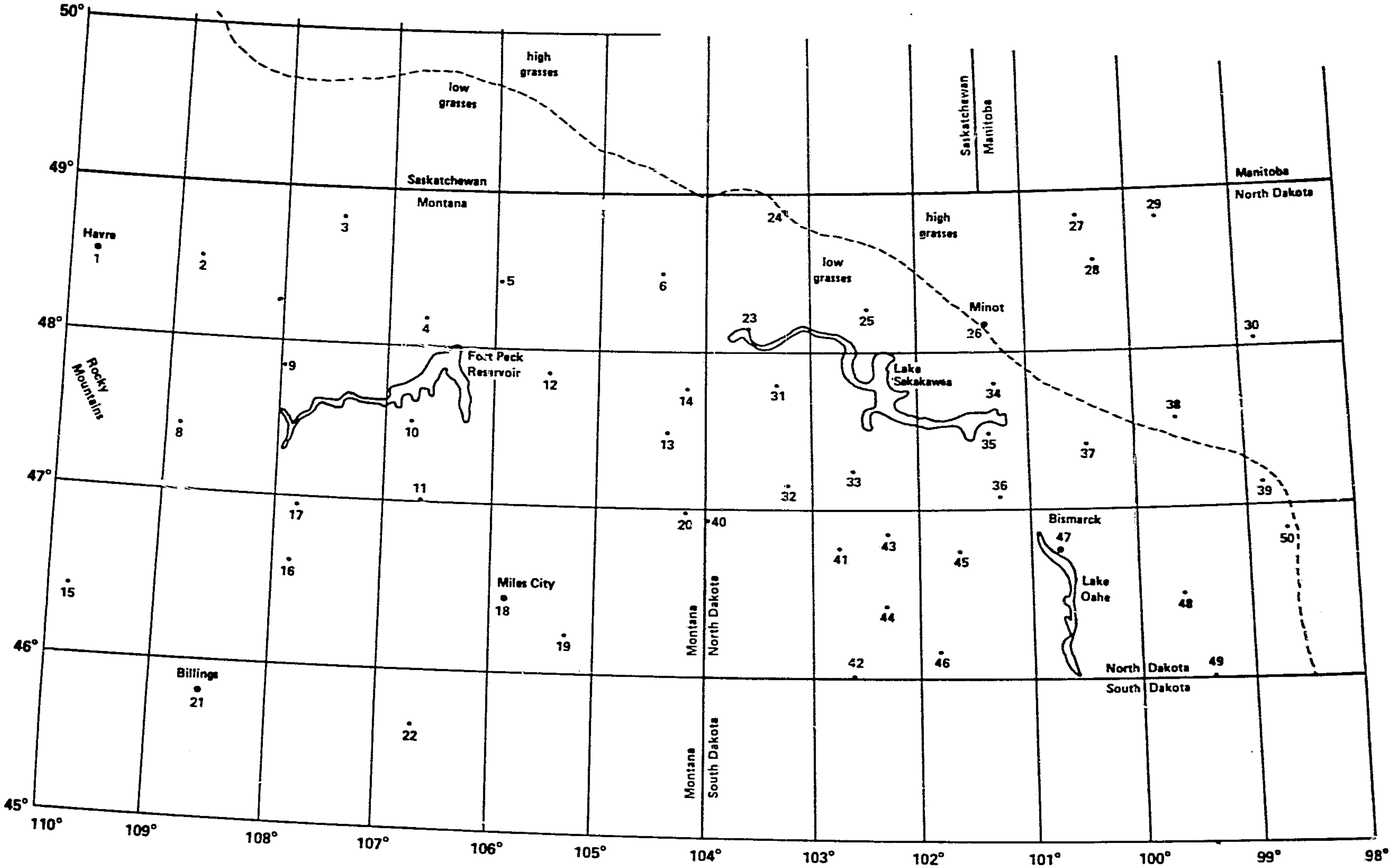

Figure 2. The North Dakota-Montana snow/microwave study area. Numbered locations represent city airports reporting snow depth (Foster et al., 1980).

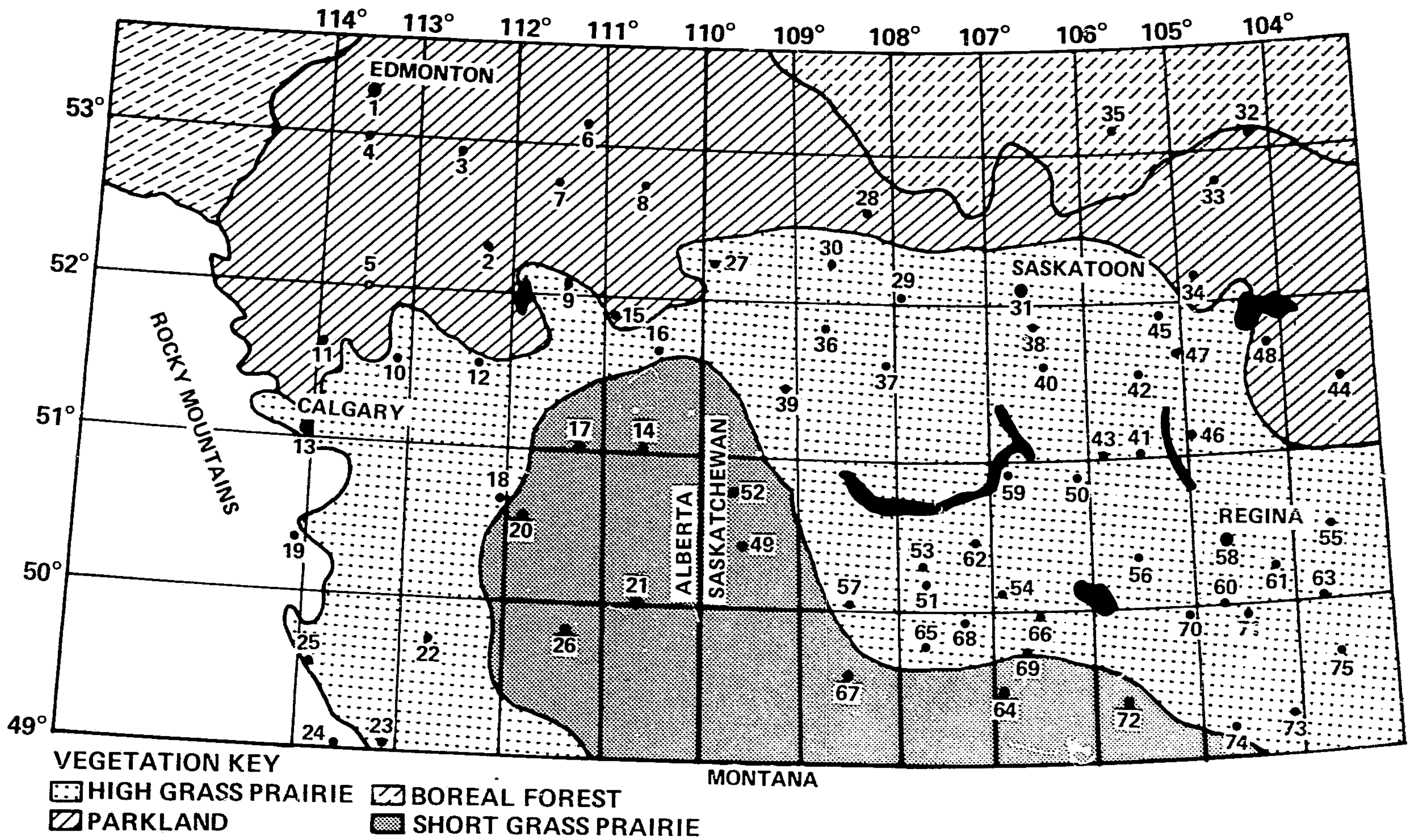

Figure 3. Canadian high plains snow/microwave study area. Numbered locations represent snow course sites (Rango et al., 1979).

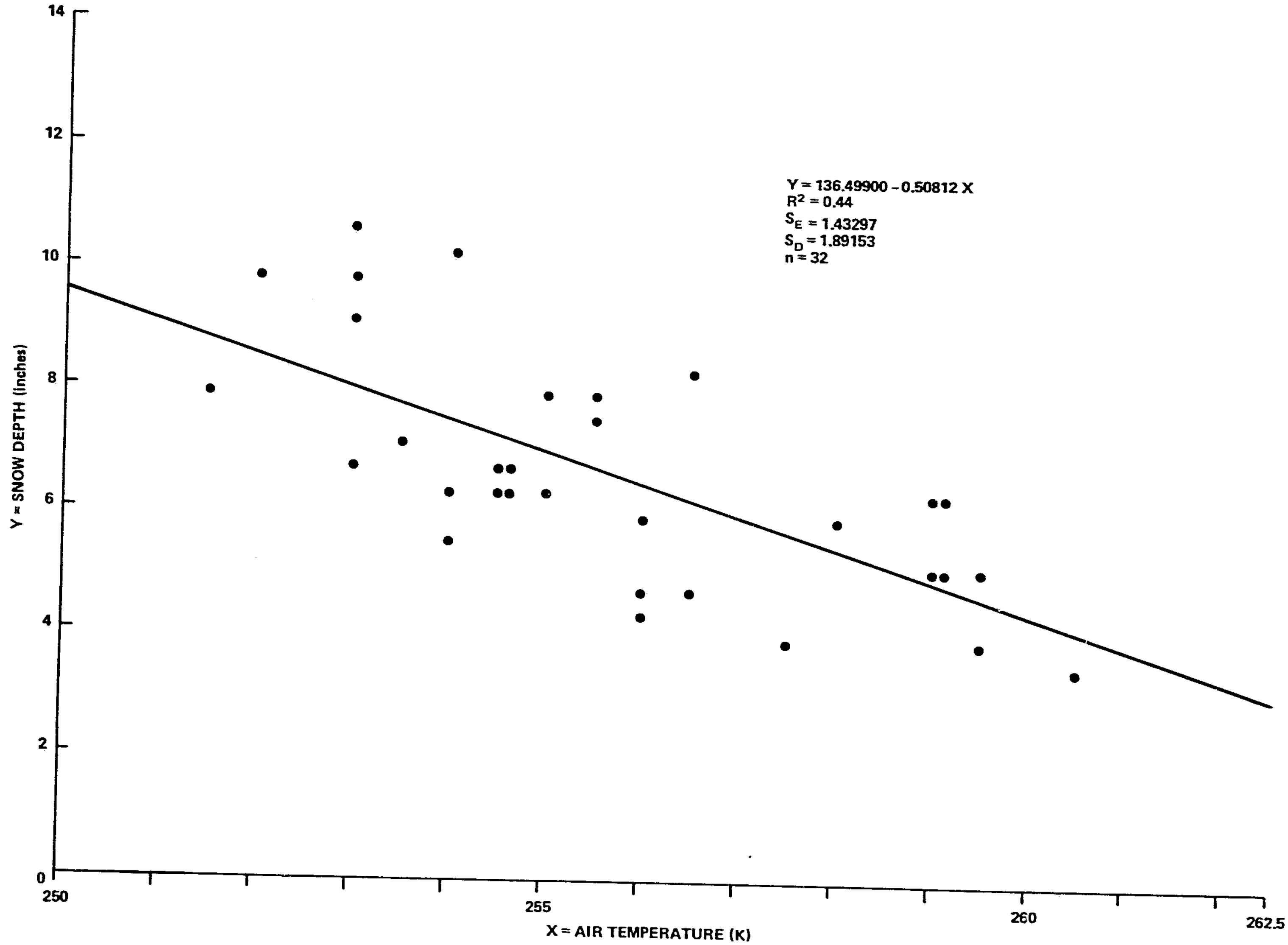

Figure 4. Surface air temperature versus snow depth on the steppes of central Russia. Air temperature and snow depth data from January 20, 1976, summarized by 1-degree latitude/longitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

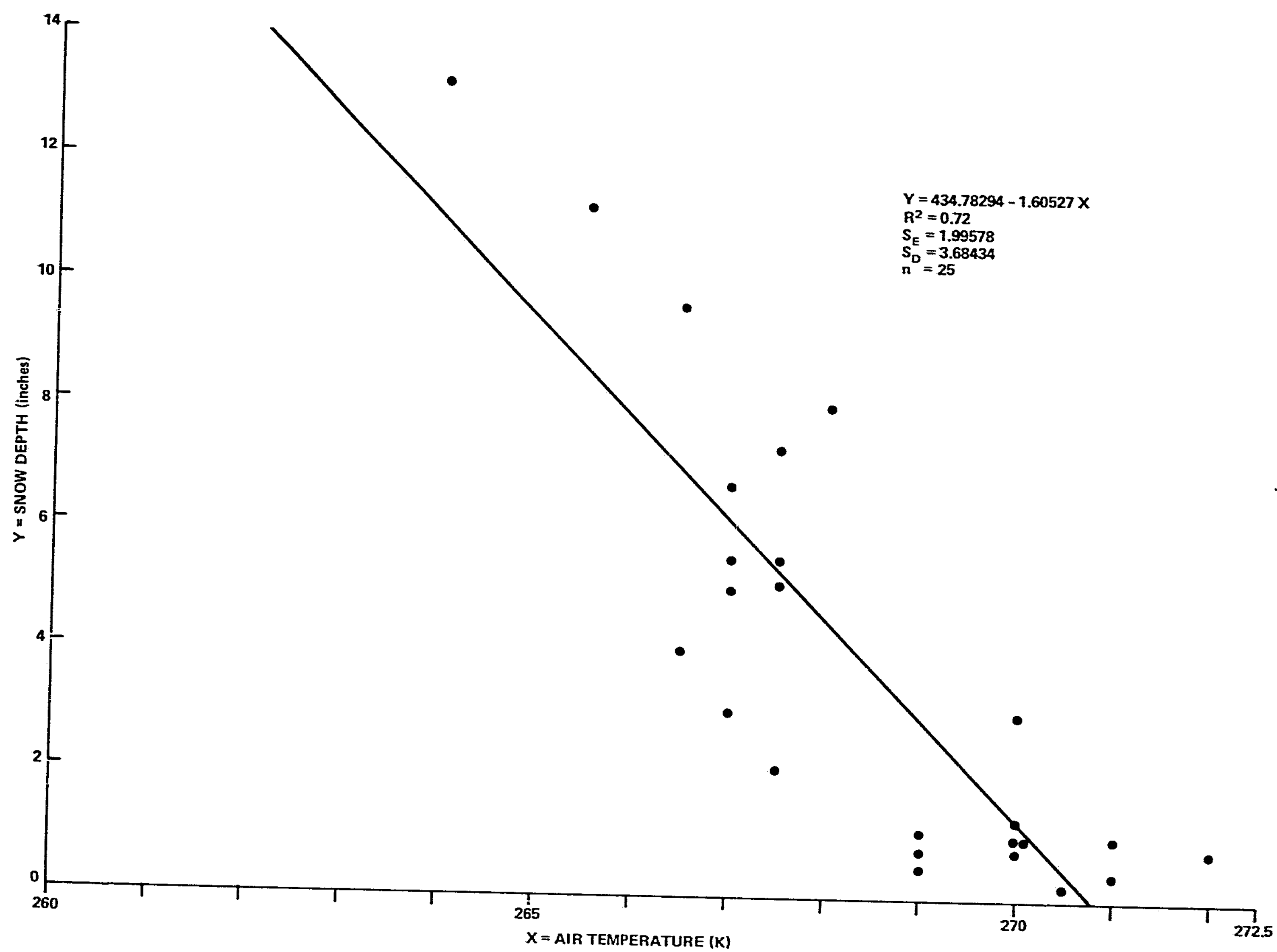

Figure 5. Surface air temperature versus snow depth on the high plains of Montana and North Dakota. Air temperature and snow depth data from March 15, 1965, summarized by 1-degree latitude/longtitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

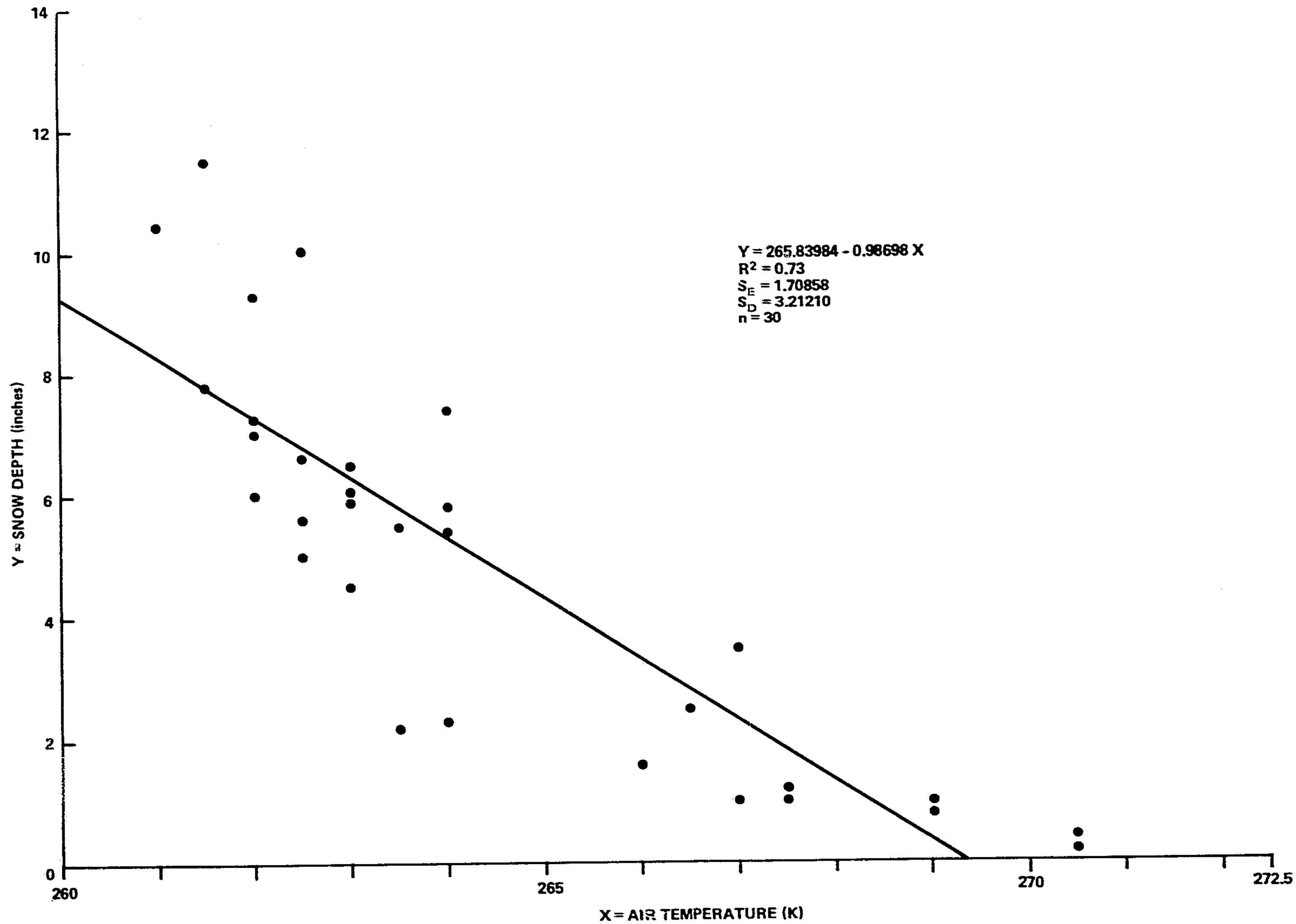

Figure 6. Surface air temperature versus snow depth on the Canadian high plains. Air temperature and snow depth data from March 15, 1976, summarized by 1-degree latitude/longitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

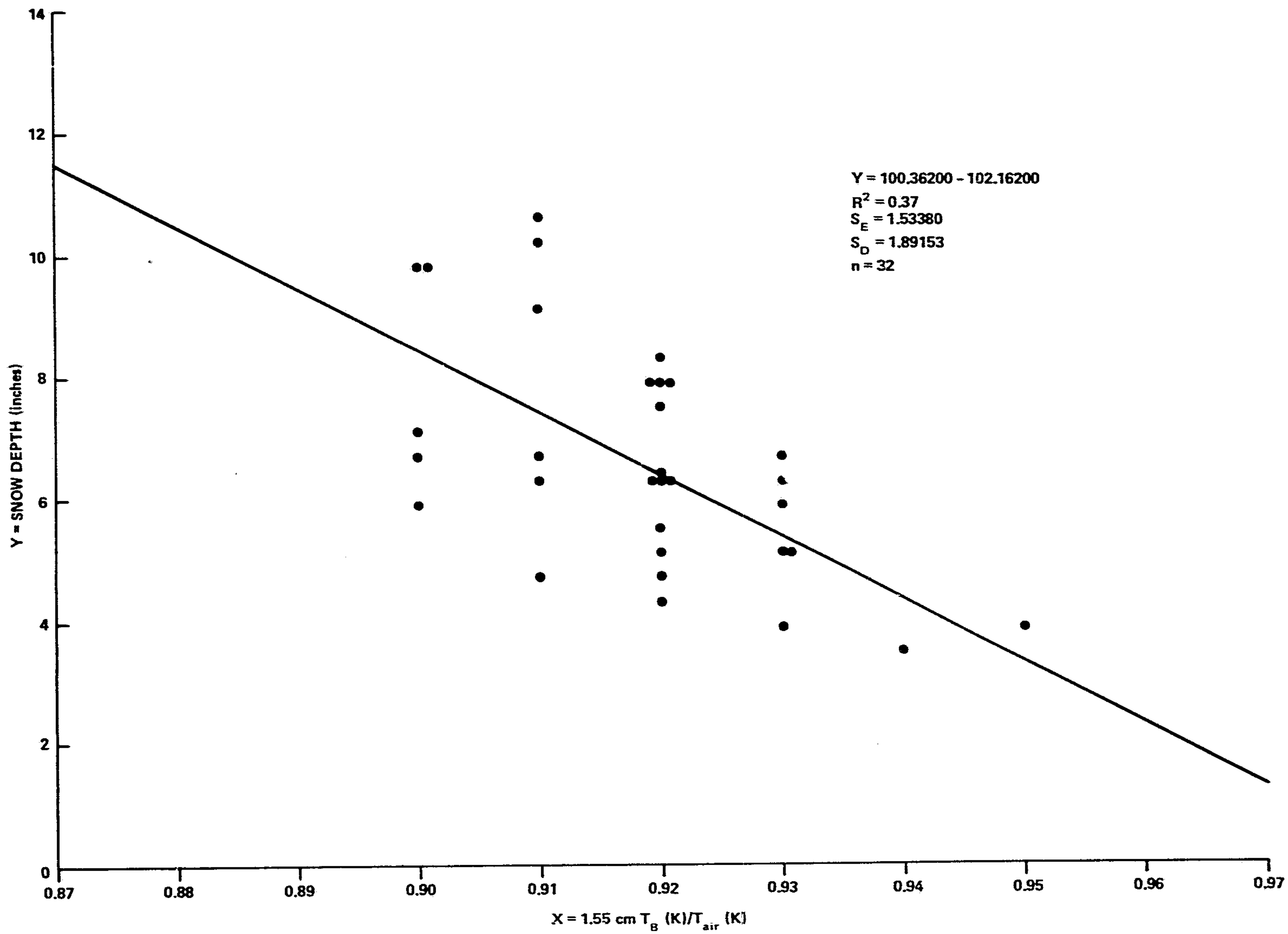

Figure 7. T_B/T_{air} versus snow depth on the steppes of central Russia. Nimbus 5 T_B, snow depth, and average air temperature data from January 20, 1976, summarized by 1-degree latitude/longitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

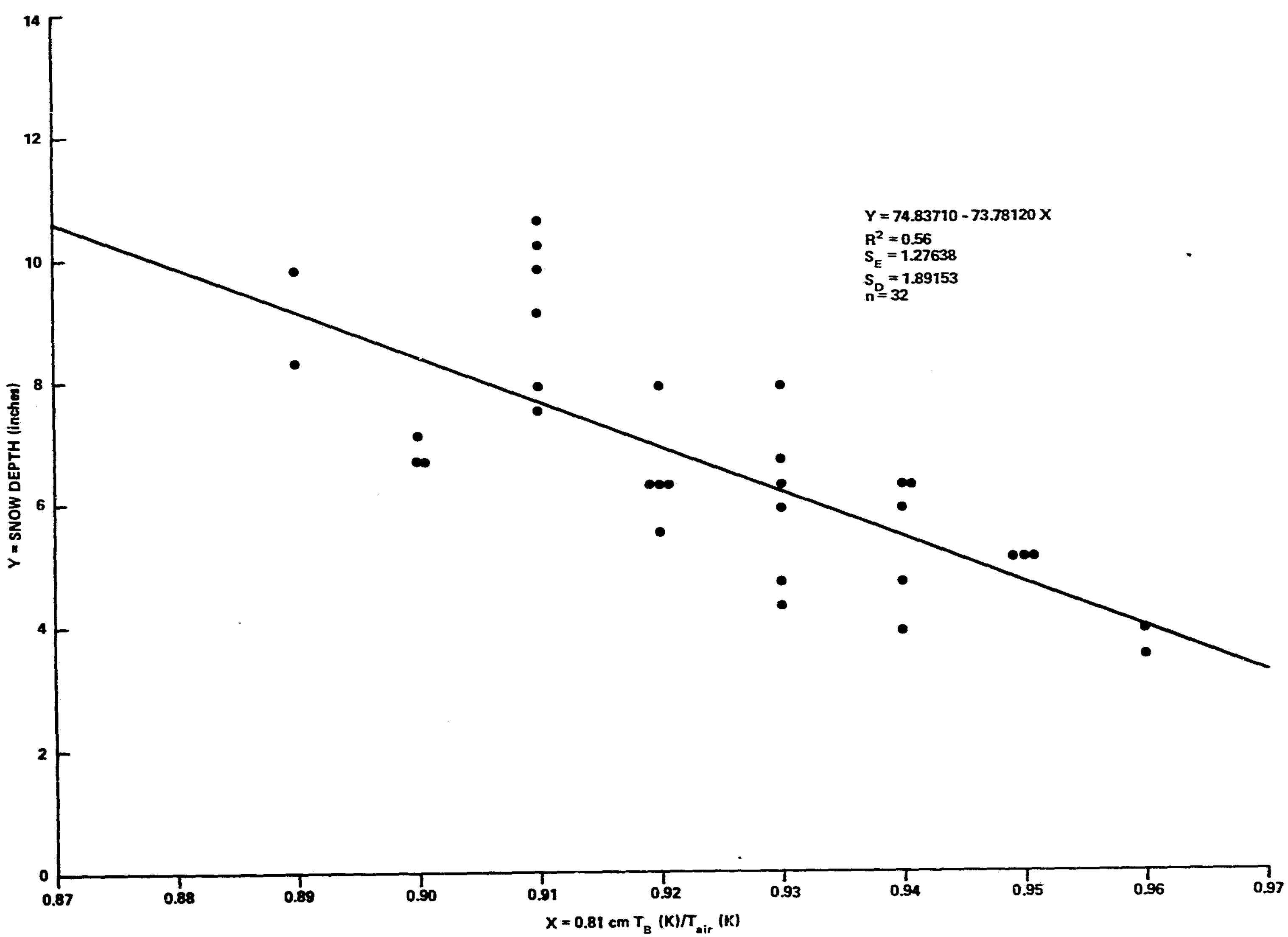

Figure 8. T_B/T_{air} versus snow depth on the steppes of central Russia. Nimbus 6 T_B, snow depth, and average air temperature data from January 1976, summarized by 1-degree latitude/longitude grid. (K^2 = coefficient of determination, S_E = standard error, S_D - standard deviation, and n = number of grids.)

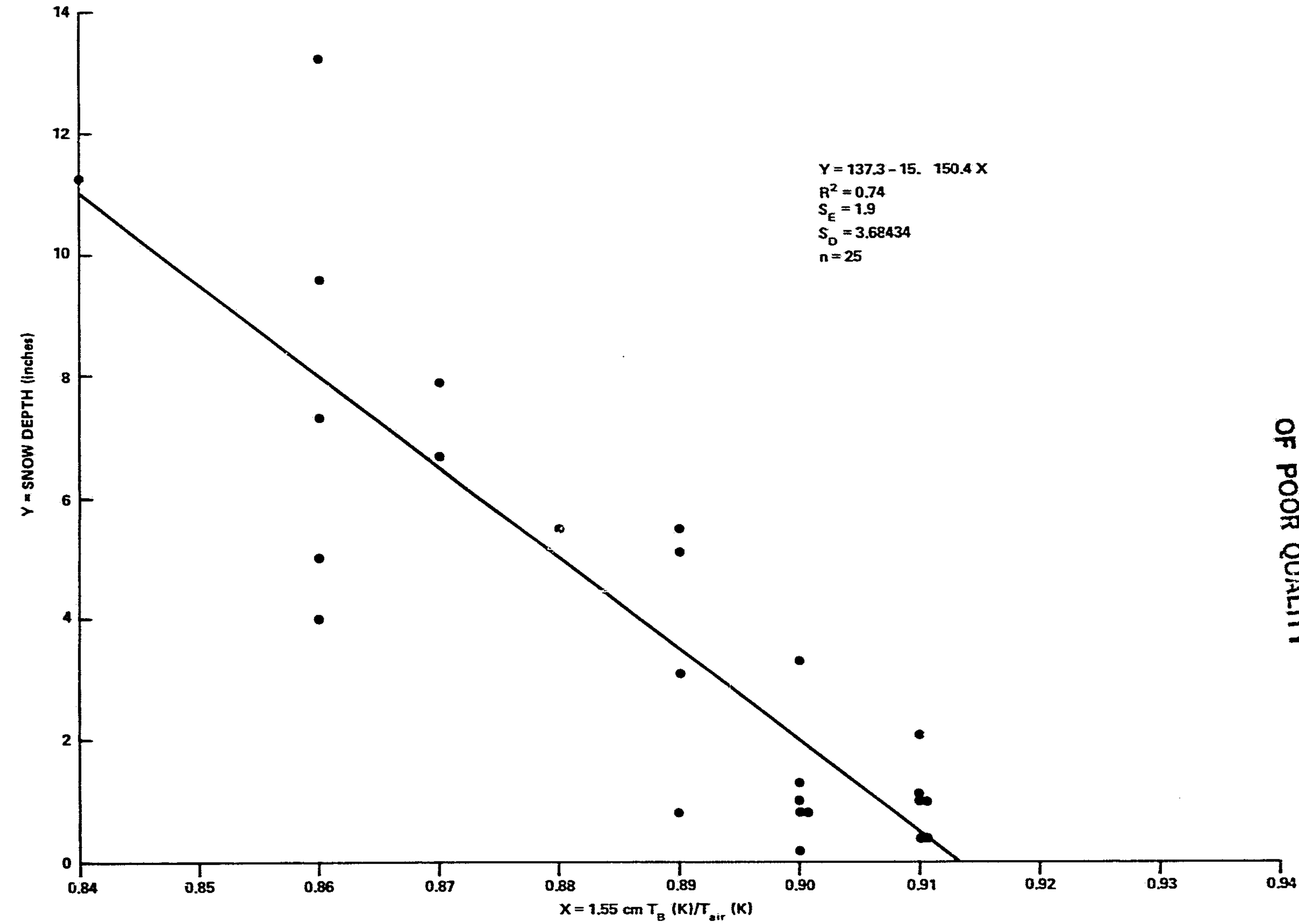

Figure 9. T_B/T_{air} versus snow depth on the high plains of Montana and North Dakota. Nimbus 6 T_B and average air temperature data from March 14, 1976. Snow depth data from March 15, 1976. Snow depth, T_B, and T_{ave} data summarized by 1-degree latitude/longitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

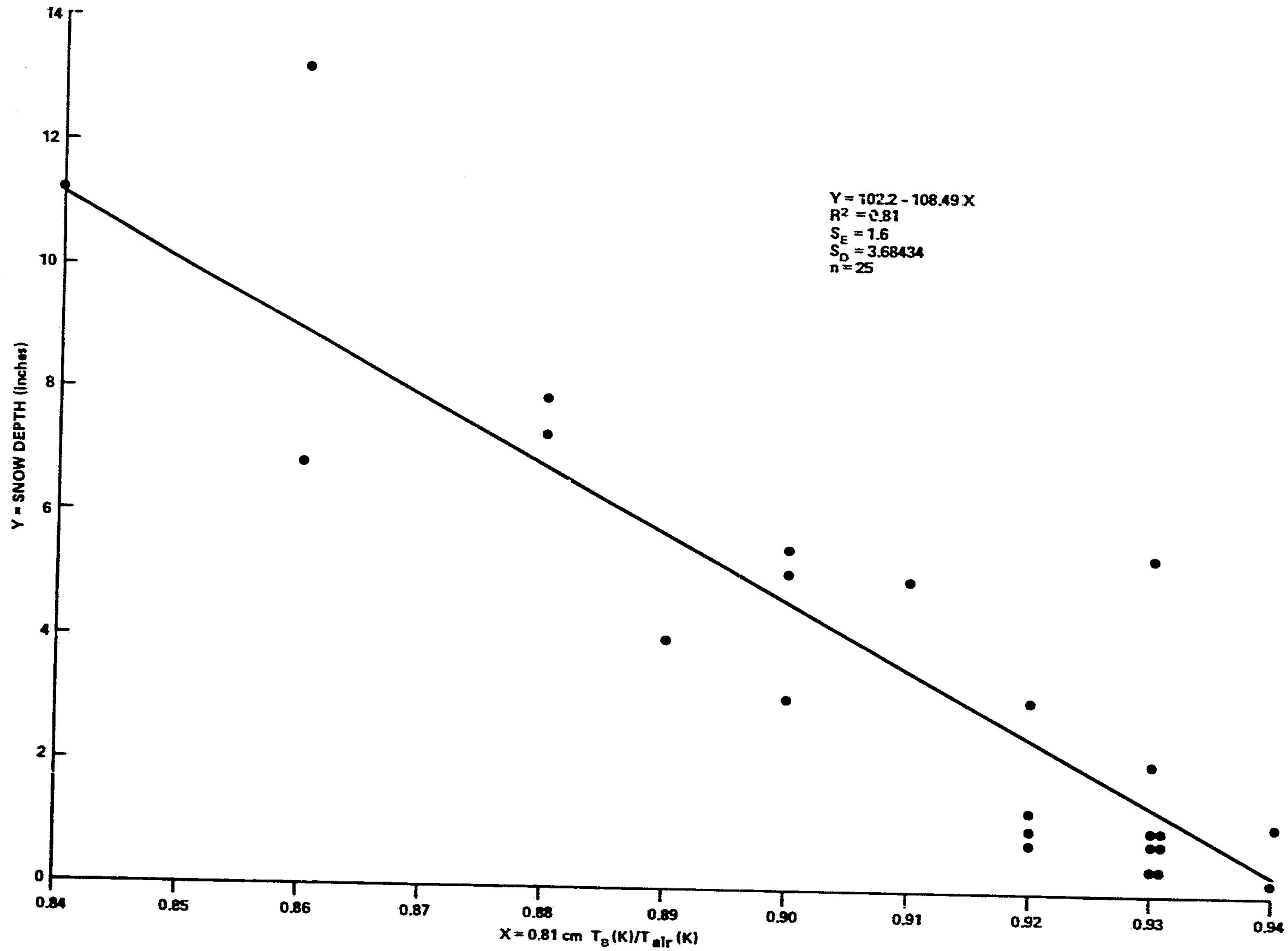

Figure 10. T_B/T_{air} versus snow depth on the high plains of Montana and North Dakota. Nimbus 6 T_B, snow depth, and average air temperature data from March 15, 1976, summarized by 1-degree latitude/longitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

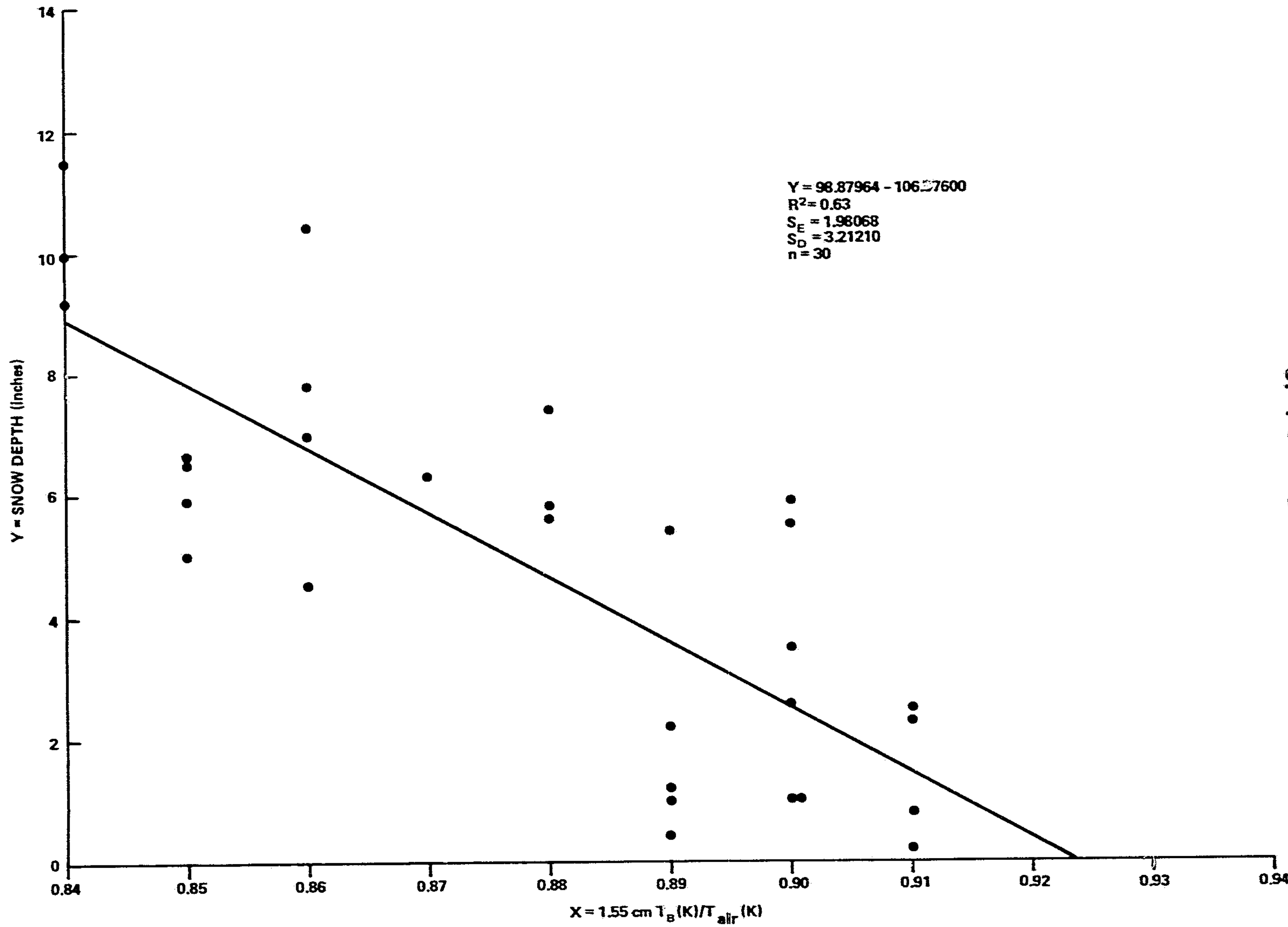

Figure 11. T_B/T_{air} versus snow depth on the high plains of Canada. Nimbus 5 T_B and average air temperature data from March 14, 1976. Snow depth data from March 15, 1976, Snow depth, T_B, and T_{min} data summarized by 1-degree latitude/longtitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)

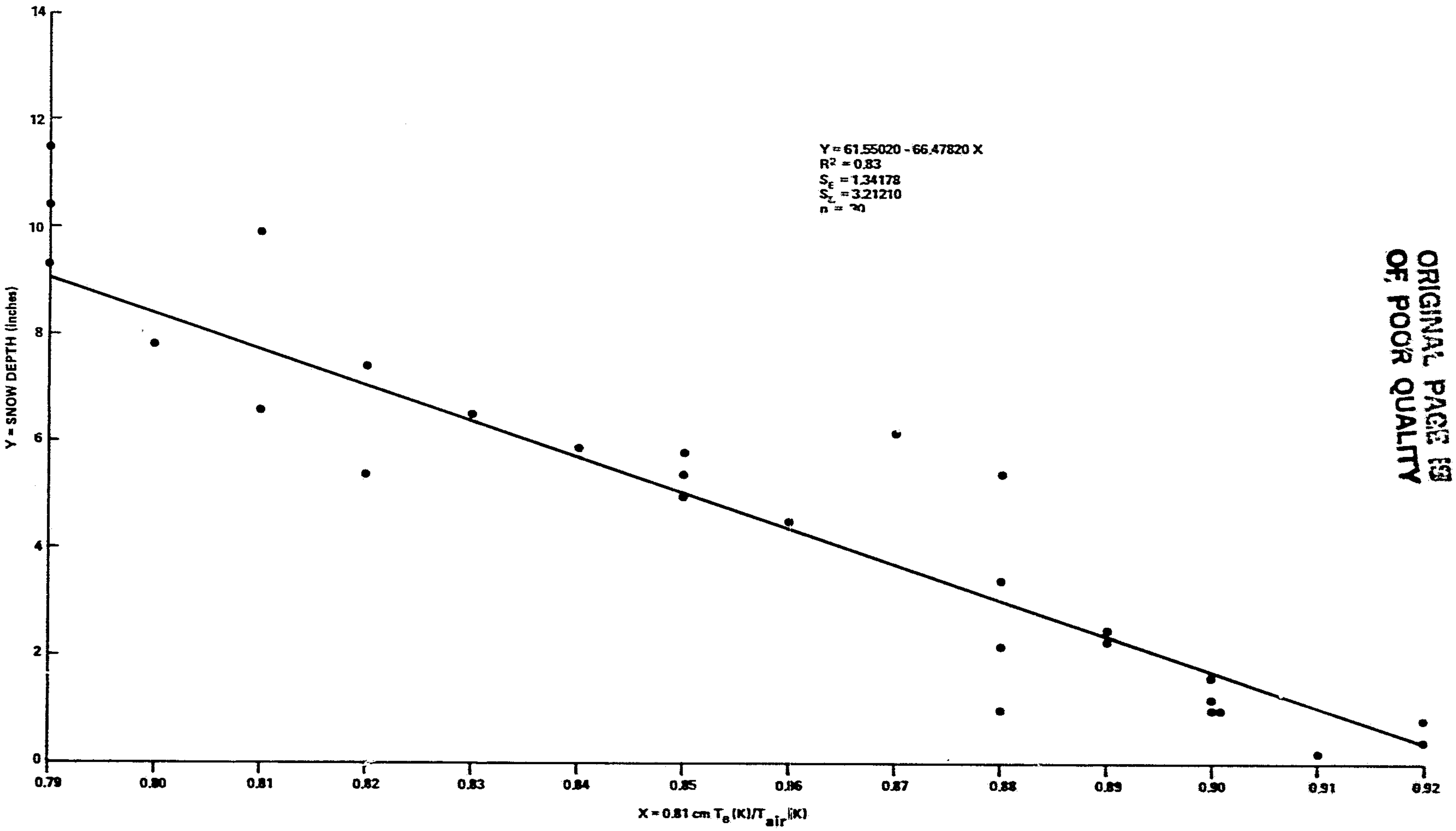

Figure 12. T_B/T_{air} versus snow depth on the high plains of Canada. Nimbus 6 T_B, snow depth, and average air temperature data from March 15, 1976, summarized by 1-degree latitude/longtitude grid. (R^2 = coefficient of determination, S_E = standard error, S_D = standard deviation, and n = number of grids.)