UDC 551.524.35:551.578.46:551.509.331

The Influence of Average Snow Depth on Monthly Mean Temperature Anomaly

A. JAMES WAGNER—*Long-Range Prediction Group, National Meteorological Center, NOAA, Suitland, Md.*

ABSTRACT—Linear regression equations relating monthly mean temperature anomaly to average monthly snow depth and its anomaly were derived for 15 selected stations, using 8 yr of data. It was found that, depending on the characteristics of the station location, from about 10 to 55 percent of the variance of the monthly mean temperature anomaly could be explained in terms of the average monthly snow depth or its anomaly.

1. INTRODUCTION

For a long time, we have known that the presence of a snow cover will make the temperature lower than it would have been with bare ground. This cooling effect is due both to lower minima, caused by the enhancement of nocturnal radiation over snow due to its higher emissivity (closer approximation to an ideal blackbody radiator than bare ground) whenever clear skies and light winds prevail, and to lower maxima, when a larger portion of the incoming solar radiation is reflected or when heat is extracted from the air to melt the snow. Namias (1962) estimated that as much as 10°F of anomalous cooling on a monthly basis was caused by an extensive snow cover over the central United States in February and March of 1960. Adem (1964) has incorporated the effects of anomalous snow cover into his thermodynamic numerical model, using data later published by Dickson and Posey (1967).

Klein and Marshall (1973) recently found that the existence of a snow cover alone explained about 40 percent of the variance of daily maximum and minimum temperatures for the winter months, December through February, but that the snow cover variable added only 1–3 percent to the variance explained by the previous day's maximum and minimum temperatures. The mere presence or absence of a shallow snow cover does not usually result in a sudden change in temperature at a station, but the depth of the snow, at least up to several inches, is also important in specifying how much lower the temperature will be than if the snow were not there. There are several reasons for this.

With snow depths of only a few inches, there is probably a small amount of conduction and radiation of heat from the ground below. As suggested by Kung et al. (1964), the depth of snow up to about 5 in. is also probably related to the completeness of cover, especially with regard to vegetation, roofs, and naturally sloping areas.

In addition to these effects, there are additional statistical factors that must be considered when one is concerned with snow cover and temperature anomaly over periods of a few weeks or longer. The deeper the average snow depth is over a month, for example, the less likely the occurrence of days with bare ground and the more likely it is that the snow cover was augmented frequently during the month. Fresh snow has a higher albedo than older snow, which tends to be dirtier and more packed.

An additional factor may result in the recording of abnormally low minimum temperatures over very deep snow. Thermometers in the standard instrument shelter record the temperature about 5 or 6 ft above the ground. When there are several feet of snow on the ground, the thermometers are much closer to the radiating surface. Oke (1970) found that on a calm, clear night the coldest temperatures were found just a few centimeters above the radiating surface.

2. DATA AND PROCEDURE

Several instances of record or near-record low monthly mean temperature, associated with or following exceptionally heavy snowfalls, have been noted at such diverse locations as Flagstaff and Winslow, Ariz. (Stark 1968, Wagner 1968), Albany, N.Y. (Posey 1970, Wagner 1970), and Lander, Wyo., and Milford, Utah (Taubensee 1973, Wagner 1973). On the other hand, temperatures are often anomalously low for a few days following a snowfall, but the effect does not last unless the snow cover is deep initially or is renewed or added to by subsequent storms. The cooling effect over a monthly period of an initial snow cover has frequently been subjectively overestimated because of rapid melting of the snow.

We decided to estimate the average snow cover throughout a month from the file of weekly North American snow depth maps kept in the Long Range Prediction Group and its predecessor, the Extended Forecast Division, since 1965. This study was made at 15 temperature verification stations located near or just north of the mean midwinter snow cover limit, to obtain a sample with varying depths as well as bare ground. Data from the months of November through March from 1965 through 1973 were used; October was also included for three stations in the Northern Rocky Mountains. The normal snow cover during each month was interpolated from data in an unpublished report by Dickson (1962) giving the normal depth of

TABLE 1.—*Linear regression equations relating monthly mean temperature anomaly,* ΔT (°*F*)*, to monthly mean snow depth anomaly,* ΔS (*in.*)

Station	Equation	Correlation coefficient
Boston, Mass.	$\Delta T=-0.9-0.48\Delta S$	−0.27
Albany, N.Y.	$\Delta T=-0.7-0.67\Delta S$	−.56
Cleveland, Ohio	$\Delta T=-0.4-1.67\Delta S$	−.51
Grand Rapids, Mich.	$\Delta T=0.0-0.61\Delta S$	−.41
Des Moines, Iowa	$\Delta T=0.3-1.57\Delta S$	−.48
Minneapolis, Minn.	$\Delta T=2.0-0.42\Delta S$	−.46
Bismarck, N. Dak.	$\Delta T=-0.7-1.17\Delta S$	−.50
Great Falls, Mont.	$\Delta T=0.7-3.03\Delta S$	−.61
Casper, Wyo.	$\Delta T=0.4-2.34\Delta S$	−.48
Lander, Wyo.	$\Delta T=1.5-0.88\Delta S$	−.63
Pueblo, Colo.	$\Delta T=1.7-2.50\Delta S$	−.55
Grand Junction, Colo.	$\Delta T=1.8-2.85\Delta S$	−.76
Salt Lake City, Utah	$\Delta T=0.9-1.18\Delta S$	−.41
Ely, Nev.	$\Delta T=1.6-2.13\Delta S$	−.59
Flagstaff-Winslow, Ariz.	$\Delta T=1.5-0.69\Delta S$	−.63

TABLE 2.—*Linear regression equations relating monthly mean temperature anomaly* Y (°*F*)*, to transformed monthly mean snow depth,* $X=(S)^{1/2}+(S+1)^{1/2}$ (*in.*)$^{1/2}$

Station	Equation	Correlation coefficient
Boston, Mass	$Y=1.0-0.86X$	−0.37
Albany, N.Y.	$Y=3.2-1.21X$	−.56
Cleveland, Ohio	$Y=3.4-1.82X$	−.50
Grand Rapids, Mich.	$Y=2.3-0.96X$	−.44
Des Moines, Iowa	$Y=5.3-2.33X$	−.63
Minneapolis, Minn.	$Y=4.6-0.92X$	−.51
Bismarck, N. Dak.	$Y=4.7-1.94X$	−.55
Great Falls, Mont.	$Y=5.4-2.97X$	−.57
Casper, Wyo.	$Y=2.6-1.71X$	−.35
Lander, Wyo.	$Y=4.6-1.44X$	−.54
Pueblo, Colo.	$Y=5.5-3.07X$	−.56
Grand Junction, Colo.	$Y=5.9-3.21X$	−.74
Salt Lake City, Utah	$Y=5.4-2.01X$	−.59
Ely, Nev.	$Y=5.2-2.23X$	−.59
Flagstaff-Winslow, Ariz.	$Y=4.8-1.24X$	−.65

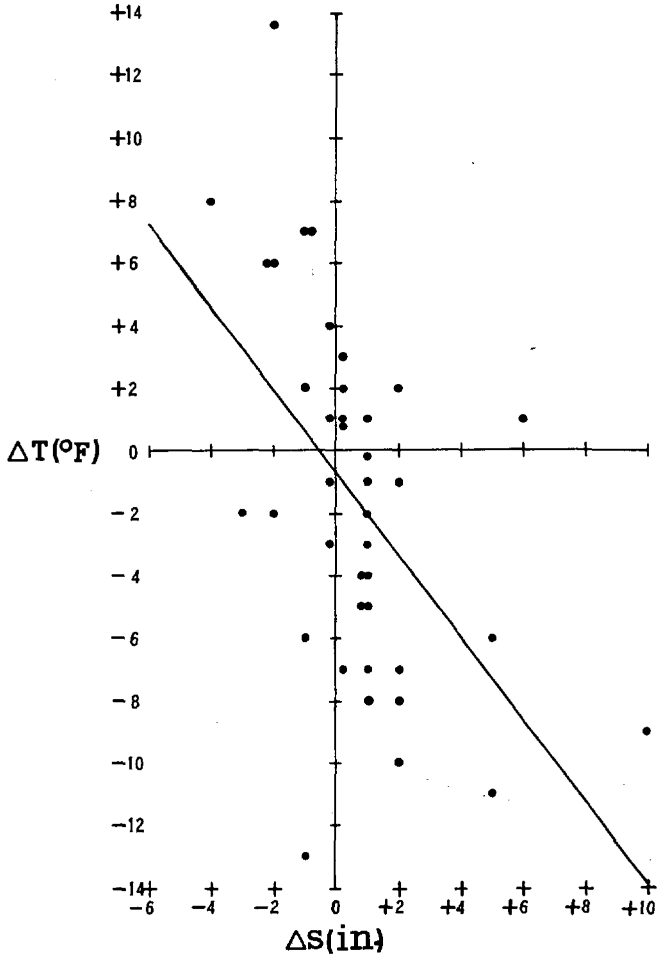

FIGURE 1.—Monthly mean temperature anomaly, ΔT(°F), as a function of the anomaly of average monthly snow depth, ΔS(in.), for Bismarck, N. Dak. The linear regression equation is given by the sloping line and individual data points are shown by dots.

snow cover at the end of each month for selected United States stations. Snow depth at Flagstaff was used in conjunction with the temperature at Winslow since snow depth normals were not readily available for Winslow.

The data were analyzed in two different ways. In the first method, the monthly mean temperature anomaly in degrees Fahrenheit was correlated with the monthly mean snow depth anomaly in inches. In the second method, the monthly mean temperature anomaly was correlated with the monthly mean snow depth itself, rather than its anomaly. Because a number of data points represented extreme snow depths at some stations, the snow depth was transformed by the relationship $X=S^{1/2}+(S+1)^{1/2}$ where S is the actual snow depth. This transformation has been found useful in statistical studies involving highly skewed quantities with a zero bound on one side.

3. RESULTS AND CONCLUSIONS

Linear regression equations for each of the stations were derived for both methods. The equations for all stations, with their correlation coefficients, are listed in tables 1 and 2. The regression graphs for a typical station, Bismarck, N. Dak., are shown in figures 1 and 2. Data points are included to give an idea of the scatter.

In general, the slopes of the equations and values of the correlation coefficients are similar for both methods. The correlation coefficients show that the amount of variance in the monthly mean temperature anomaly explained by average snow depth or its anomaly ranges from a low of about 10 percent at Boston, Mass., to more than 50 percent at Grand Junction, Colo. Some of the stations with the highest correlation coefficients, such as Albany, Lander, Grand Junction, and Winslow, are located in valleys that are fairly deep relative to the surrounding topography. One would expect that the effect on minimum temperatures due to drainage of cold air would be strongest at those locations, and the strong inversions so generated would persist well into the day and delay eventual melting of the snow.

The rather high correlation coefficient at Great Falls, Mont., may be due in part to the fact that the occurrence of precipitation is strongly negatively correlated with temperature in the Northern Plains during winter. Arctic outbreaks produce upslope motion and precipitation

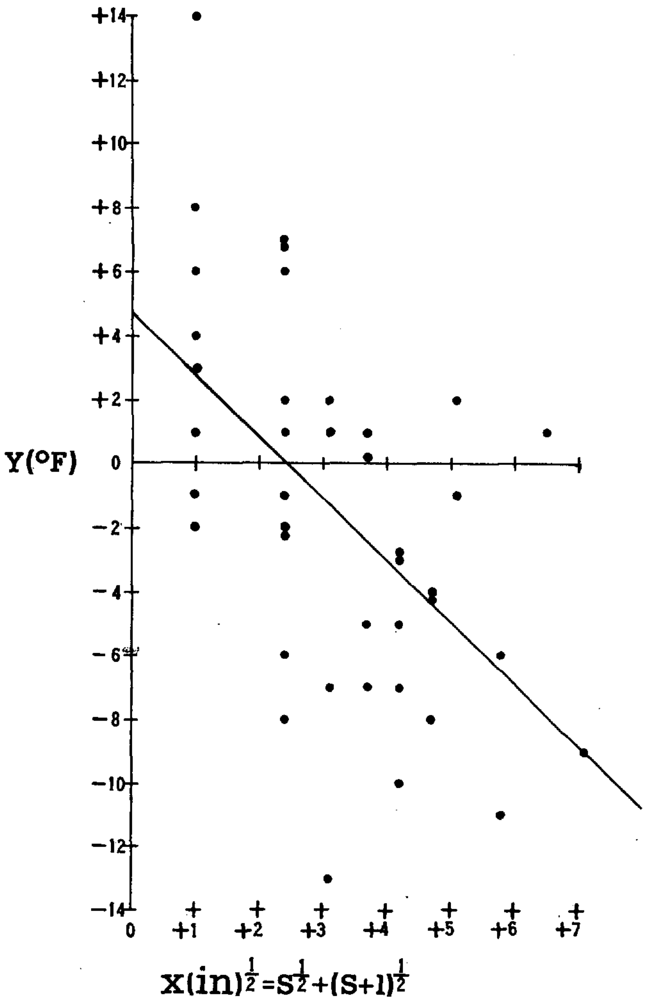

FIGURE 2.—Monthly mean temperature anomaly, Y(°F), as a function of the transformed average monthly snow depth, $X(\text{in.})^{1/2}=S^{1/2}+(S+1)^{1/2}$, for Bismarck. The graph and dots are similar to figure 1. Note, however, that the horizontal scale is different.

(nearly always snow) along the eastern slopes of the Rocky Mountains, while mild Pacific air dries as it decends into the Great Plains (Chinook winds). Any preexisting snow is rapidly melted and evaporated under these conditions.

There is an indication that the weakest correlations are found at stations with some degree of maritime influence, such as Boston, Mass., Cleveland, Ohio, and Grand Rapids, Mich. Good nocturnal radiation conditions prevail less frequently at such locations because of greater cloudiness and wind speed, and for wind directions with a water trajectory, the presence of a snow cover on land would have little effect.

In their transformed snow depth form (table 2), the regression equations show that the expected temperature with no snow cover at all ($S=0$, $X=1$) is above normal at every station, usually by 2° or 3°F. This result is certainly not surprising but may be of use in monthly or long-period prediction of temperature and snowfall.

In conclusion, one or two cautionary statements should be made. As stated earlier, the stations investigated were chosen near or just north of the average snow-cover limit for the midwinter months. The overall results shown here would not necessarily be applicable to stations far north or well south of the mean winter snow-cover limit, and as seen in this paper, there is considerable variation in the coefficients of the regression equation from station to station. It should also be noted that even though we have specified snow depth as the independent variable and temperature as the dependent variable, the amount of snow falling in a month obviously also depends on the mean temperature, particularly in regions where the winter precipitation normally consists of both rain and snow.

ACKNOWLEDGMENTS

The author wishes to thank Mary Abernathy for computing the regression equations and Mike Gaidurgis for drafting the figures.

REFERENCES

Adem, Julian, "On the Physical Basis for the Numerical Prediction of Monthly and Seasonal Temperatures in the Troposphere-Ocean-Continent System," *Monthly Weather Review*, Vol. 92, No. 3, Mar. **1964**, pp. 91–103.

Dickson, Robert R., "Snow Cover in the United States," unpublished research report, Extended Forecast Branch, U.S. Weather Bureau, Sept. **1962**, 5 pp. + charts.

Dickson, Robert R., and Posey, Julian, "Maps of Snow-Cover Probability for the Northern Hemisphere," *Monthly Weather Review*, Vol. 95, No. 6, June **1967**, pp. 347–353.

Klein, William H., and Marshall, Frederick, "Screening Improved Predictors for Automated Max/Min Temperature Forecasting," *Preprint Volume of the Third Conference on Probability and Statistics in Atmospheric Science, June 19–22, 1973, Boulder, Colorado*, American Meteorological Society, Boston, Mass., **1973**, pp. 36–43.

Kung, Ernest C., Bryson, Reid A., and Lenschow, Donald H., "Study of a Continental Surface Albedo on the Basis of Flight Measurements and Structure of the Earth's Surface Cover Over North America," *Monthly Weather Review*, Vol. 92, No. 12, Dec. **1964**, pp. 543–564.

Namias, Jerome, "Influences of Abnormal Surface Heat Sources and Sinks on Atmospheric Behavior," *Proceedings of the International Symposium on Numerical Weather Prediction, Nov. 7–13, 1960, Tokyo, Japan*, Meteorological Society of Japan, Tokyo, Mar. **1962**, pp. 615–627.

Oke, T. R., "The Temperature Profile Near the Ground on Calm Clear Nights," *Quarterly Journal of the Royal Meteorological Society*, Vol. 96, No. 407, London, England, Jan. **1970**, pp. 14–23.

Posey, Julian W., "The Weather and Circulation of December 1969—Record December Snowfall in the Northern and Central Appalachian Mountains," *Monthly Weather Review*, Vol. 98, No. 3, Mar. **1970**, pp. 253–258.

Stark, L. P., "The Weather and Circulation of December 1967—Temperature Reversal Associated With Intramonthly Amplification," *Monthly Weather Review*, Vol. 96, No. 3, Mar. **1968**, pp. 190–195.

Taubensee, Robert E., "Weather and Circulation of December 1972—Record Cold in the West," *Monthly Weather Review*, Vol. 101, No. 3, Mar. **1973**, pp. 281–286.

Wagner, A. James, "The Weather and Circulation of January 1968—Extreme Cold Followed by Rapid Warming at Mid-Month," *Monthly Weather Review*, Vol. 96, No. 4, Apr. **1968**, pp. 262–267.

Wagner, A. James, "The Weather and Circulation of January 1970—Record Cold in the Eastern Third of the Nation and Record Rainfall in the Pacific Northwest," *Monthly Weather Review*, Vol. 98, No. 4, Apr. **1970**, pp. 328–334.

Wagner, A. James, "The Weather and Circulation of January 1973—Strong Warming Trend Around Midmonth," *Monthly Weather Review*, Vol. 101, No. 4, Apr. **1973**, pp. 381–386.

[*Received June 12, 1973; revised July 20, 1973*]