Snow Cover and Temperature Relationships in North America and Eurasia

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ABSTRACT

In this study the snow cover extent during the autumn months in both North America and Eurasia has been related to the ensuing winter temperature as measured at several locations near the center of each continent. The relationship between autumn snow cover and the ensuing winter temperatures was found to be much better for Eurasia than for North America. For Eurasia the average snow cover extent during the autumn explained as much as 52% of the variance in the winter (December–February) temperatures compared to only 12% for North America. However, when the average winter snow cover was correlated with the average winter temperature it was found that the relationship was better for North America than for Eurasia. As much as 46% of the variance in the winter temperature was explained by the winter snow cover in North America compared to only 12% in Eurasia.

1. Introduction

The variable extent of snow and ice effects advancing polar air masses and as a result, climate and weather patterns are modified on both local and continental scales. The presence of snow on the ground will cause the temperature to be lower than if the ground were snow free. The cooling effect is due to both lower minima, caused by enhancement of nocturnal radiation over snow due to its higher emissivity, and to lower maxima, when a greater amount of the incoming solar radiation is reflected or when heat is extracted from the air to melt the snow (Wagner, 1973).

There have been numerous studies which have demonstrated the relationship between snow cover and temperature. Namias (1962) estimated that as much as 5.5°C of anomalous cooling was caused by an extensive snow cover in the United States during February and March of 1960. Empirical expressions for the frequency of snow cover as a function of the local temperature, precipitation and antecedent snow cover were derived by Clapp in 1967. A study by Wagner (1973) demonstrated the influence of average snow depth on monthly mean temperature anomalies for 15 selected stations in the United States. Robock (1980) has used zonally-averaged statistics relating snow cover to air temperature over land, and ice cover to ocean air temperature during an 11-year period from 1967–77. Kukla (1981) in a study from 1974–78 has shown that for three stations in North Dakota, the maximum and minimum surface air temperature were lower by ~10°C with snow on the ground than without it. Adem and Donn (1981) found snow cover to be one of the most useful predictors of a thermodynamic, long-range, forecasting model applied to prediction of anomalies of temperature and precipitation in the Northern Hemisphere. In a study using snow cover and temperature data for 60 United States cities over a 30-year period, Walsh *et al.* (1982) found that fluctuations of surface temperature are most highly correlated with departures from normal snow cover in regions that straddle the mean winter snowline.

These past studies related snow cover to temperature during the same time period, the snow cover during the winter of 1978 versus the temperature during the winter of 1978, for example. It is the purpose of this study to investigate the possibility of a relationship between the continental snow cover extent as measured in autumn and the ensuing winter temperature as observed at several locations near the center of the continent. The rationale for this is that over large snow-covered areas radiative cooling produces anticyclonic cells which enables arctic air to be transported to lower latitudes. As the snow-covered area begins to expand during the autumn, the greater snow cover allows for increasing southward penetration of the arctic air masses. There are, of course, additional meteorological parameters involved in this feedback mechanism (such as atmospheric circulation, net radiation, turbidity, precipitation and evaporation); however, this paper will only address snow cover and temperature.

2. Study area and procedures

Snow cover data were obtained for North America and Eurasia from monthly mean snow and ice charts produced by NOAA's National Earth Satellite Ser-

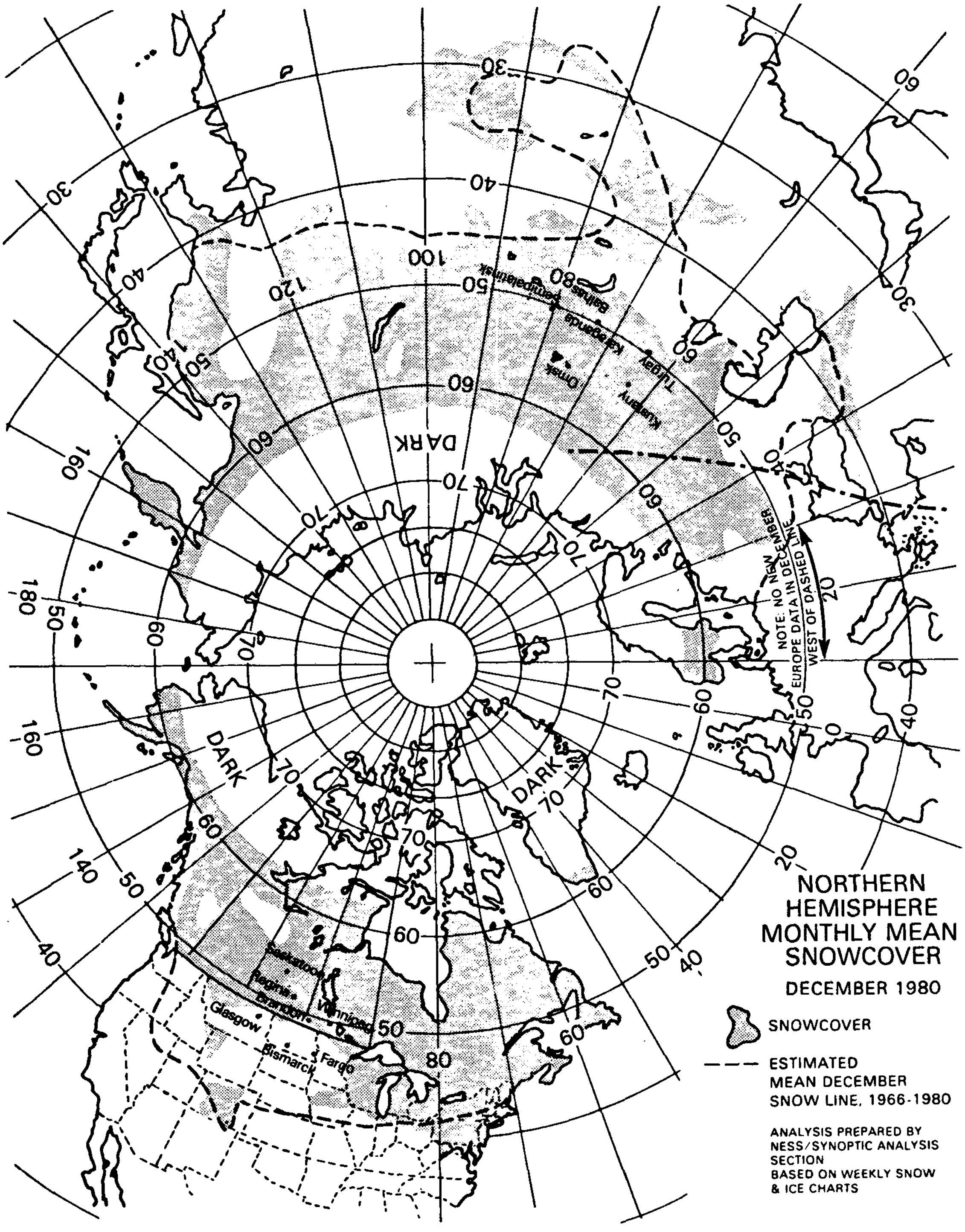

FIG. 1. Monthly mean snow cover chart for the Northern Hemisphere during December 1980.

vice. For additional information on snow cover in North America and Eurasia see Wiesnet and Matson (1976), Goodison (1981), Zhidikov (1981) and Walsh *et al.* (1982). Fig. 1 shows an example of the Northern Hemisphere monthly mean snow cover chart. These charts are drawn from satellite imagery which has been available since 1966 (Matson and Wiesnet, 1981). Because of the sometimes questionable reliability of the snow charts in the Himalayan Mountains in the late 1960's, and because there was an increasing improvement in the consistency and detail of the snow charts during the 1970's (Kukla and

Robinson, 1979) only snow cover data mapped since 1970 were used in this study. Temperature data for North America and Eurasia were obtained from meteorological stations located near the geographic center of each continent. For North America the stations that were used are Bismarck and Fargo, North Dakota; Glasgow, Montana; Saskatoon and Regina, Saskatchewan; and Winnipeg and Brandon, Manitoba. For Eurasia the stations are Balhas, Karaganda, Turgay, Kustany and Semipalatinsk, all located in the Kazakh Soviet Socialist Republic (SSR), and Omsk which is located just north of Kazakh in the Russian SSR (Fig. 1). All of these stations are in the "New Lands" agricultural region of the USSR. Mean monthly temperature data for Bismarck, Fargo and Glasgow are published in *Local Climatological Data* by the United States Department of Commerce. Monthly temperature data for Regina, Saskatoon, Brandon and Winnipeg are published by the Canadian Atmospheric Environment Service. The World Meteorological Organization publishes temperature data for the Soviet stations in *Monthly Climatic Data For The World*. Temperatures from these stations were averaged together and used as a simple indicator or index of the average winter temperature for their respective continents. Fritz (1980) used a similar approach when he used the temperature of Bismarck to serve as an index of circulation over much of western North America.

Eurasia is more than twice the size of North America and has considerably more of its land area above the Arctic Circle (National Geographic, 1970). However, the interiors of these two continents are physically quite similar. The North American stations are located between 47 and 52°N and 97 and 107°W in the Great Plains physiographic division of the United States. These interior plains are for the most part open and have only moderate relief and elevations range from 250–750 m. Vegetation consists of short-stem and long-stem prairie grasses (USDI, 1970). The Eurasian stations are located between 47 and 55°N and 64 and 80°E in the Steppes of western Siberia where elevations are generally between 100 and 600 m. This area is basically open and consists of grasses and woody shrubs (Committee for World Atlas of Agriculture, 1969). The interiors of both North America and Eurasia are important agricultural grain regions.

Tables 1 and 2 present snow cover data for North America and Eurasia respectively, for the period 1970–82. Because Eurasia is a larger continent than North America, Eurasian snow cover variations exhibit a wider range of absolute values. Temperatures from the seven North American stations and the six Eurasian stations were averaged together and plotted against the autumn snow cover for North America and Eurasia respectively. The data were analyzed by using simple linear regression and correlation analysis. Different time period regimes from September through December were used for snow-covered areas (Table 3). Because an anomalous early season transitory snow event could cause a bias in tabulating the monthly mean snow-covered area, time intervals of at least two months were used to calculate the mean snow-covered area. In this way the mean snow-covered area values during the autumn for North America and Eurasia were correlated with the mean winter (December–February) temperatures for the interiors of North America and Eurasia, respectively. In addition, the mean snow-covered area was plotted against the mean January temperature to determine if a better relationship existed with the coldest winter month than with the entire winter. Also, the mean winter snow cover was correlated with the mean winter temperature for both continents.

TABLE 1. Snow cover data for North America (10^6 km^2).

Date	Sep	Oct	Nov	Dec	Jan	Feb
1969–70	3.0	4.5	13.1	14.7	17.3	15.6
1970–71	2.5	7.7	13.7	16.0	16.6	16.7
1971–72	3.9	8.5	13.4	15.9	16.8	16.6
1972–73	5.6	10.7	13.0	17.2	16.9	17.0
1973–74	4.2	7.2	14.4	16.6	16.8	16.5
1974–75	3.2	9.7	13.8	16.2	17.0	17.2
1975–76	3.9	7.8	14.1	16.2	16.6	16.6
1976–77	3.1	9.7	12.9	15.3	17.6	16.5
1977–78	3.9	8.1	12.0	15.9	18.2	18.9
1978–79	4.8	9.6	14.3	17.4	18.3	18.8
1979–80	3.2	6.4	11.4	14.4	17.0	18.6
1980–81	3.8	6.6	13.2	14.3	15.8	15.4
1981–82	3.5	8.0	12.7	16.5	18.2	17.6
Average	3.7	7.6	13.2	15.8	17.1	16.8
Standard deviation	0.8	1.8	0.8	0.9	0.6	1.2

TABLE 2. Snow cover data for Eurasia (10^6 km^2).

Date	Sep	Oct	Nov	Dec	Jan	Feb
1969–70	0.5	7.2	18.8	22.4	26.7	24.5
1970–71	0.1	6.5	19.0	24.7	27.2	30.1
1971–72	2.4	12.0	21.4	26.0	31.4	34.4
1972–73	4.3	14.9	22.8	27.1	30.3	31.2
1973–74	2.1	10.0	23.2	29.0	28.6	29.2
1974–75	1.6	10.7	20.0	24.3	27.7	28.5
1975–76	2.0	7.9	19.9	27.8	27.9	29.3
1976–77	1.3	21.9	22.9	25.8	32.3	28.4
1977–78	1.8	12.5	19.9	28.7	32.2	33.9
1978–79	2.5	14.5	18.9	27.6	32.7	31.3
1979–80	1.2	9.2	18.1	23.2	28.0	30.9
1980–81	1.6	7.4	20.4	23.1	25.4	27.5
1981–82	1.1	8.2	21.3	26.5	29.3	27.6
Average	1.6	10.0	20.3	25.9	28.9	29.7
Standard deviation	1.0	4.7	1.7	2.1	2.3	2.7

TABLE 3. Coefficient of correlation (r) and determination (r^2) for snow cover versus temperature (1970–82). $\mathcal{S}$ is significance at 95% level.

		Mean snow cover						
		Sep–Oct	Oct–Nov	Sep–Nov	Oct–Dec	Sep–Dec	Nov–Dec	Dec–Feb
*North America*** (Average of 7 stations)								
December–February	r	−0.19	−0.32	−0.20	−0.30	−0.29	−0.34	−0.68$\mathcal{S}$
	r^2	0.04	0.10	0.04	0.09	0.08	0.12	0.46
January	r	0.21	−0.02	0.20	0.04	0.10	−0.05	−0.41
	r^2	0.04	0.00	0.04	0.00	0.01	0.00	0.17
*Eurasia** (Average of 6 stations)								
December–February	r	−0.60$\mathcal{S}$	−0.72$\mathcal{S}$	−0.64$\mathcal{S}$	−0.65$\mathcal{S}$	−0.59$\mathcal{S}$	−0.42	−0.34
	r^2	0.36	0.52	0.41	0.42	0.35	0.18	0.12
January	r	−0.60$\mathcal{S}$	−0.63$\mathcal{S}$	−0.62$\mathcal{S}$	−0.56$\mathcal{S}$	−0.56$\mathcal{S}$	−0.33	−0.44
	r^2	0.36	0.40	0.38	−0.31	0.31	0.11	0.19

** North American stations = Bismarck, Fargo, Glasgow, Regina, Winnipeg, Saskatoon and Brandon.
* Eurasian stations = Karaganda, Kustany, Omsk, Semipalatinsk, Turgay, and Balhas.

3. Results

Table 3 presents the coefficient of correlation r and the coefficient of determination r^2 values for North America and Eurasia for the years 1970–82. The correlations are considerably higher for Eurasia than for North America. For Eurasia the r^2 values show that the amount of variance in the winter temperature, explained by the snow cover extent in autumn ranges from a low of 18% for November and December to a high of 52% for October and November. For North America, the amount of variance explained ranges from only ~4% for September and October to ~12% for November and December. Fig. 2 shows the regression analysis for Eurasia. Using the temperature of the coldest month (January) to plot against snow cover did not improve the correlations (Table 3).

Most of the correlations obtained by relating autumn snow cover to winter temperature were significant at the 95% level for the Eurasian data (Table 3); whereas, none of the correlations were found to be significant at even the 90% level for the North

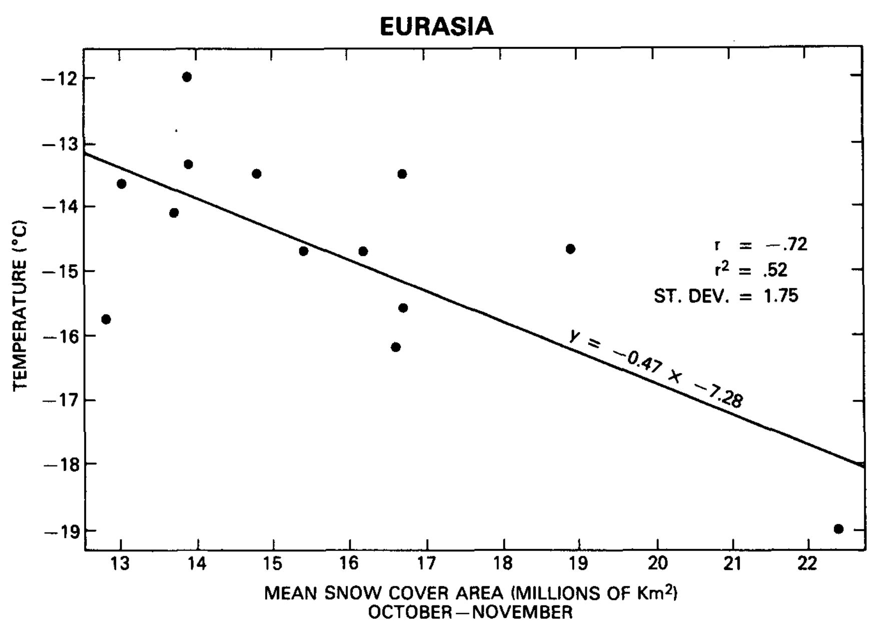

FIG. 2. Regression analysis of Eurasia relating October–November snow cover to December–February temperature.

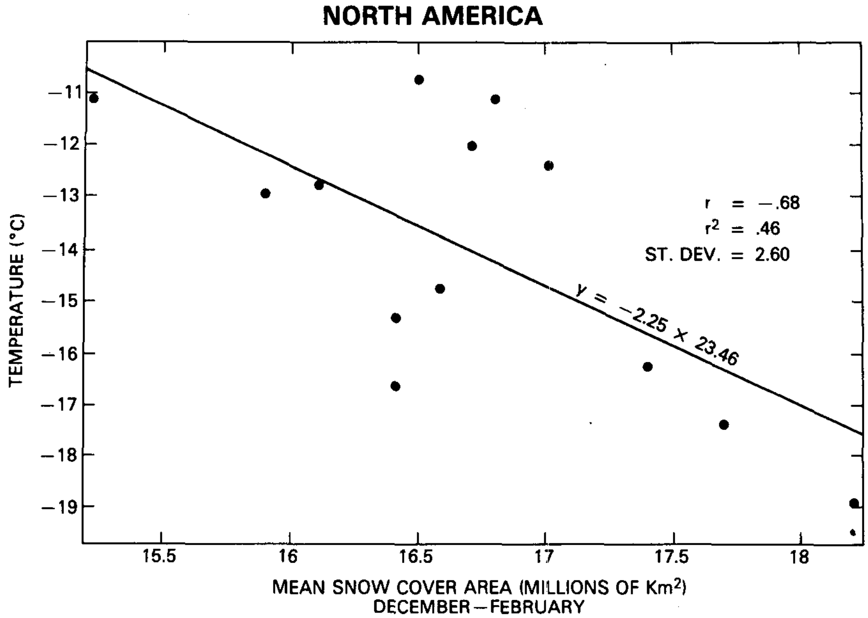

FIG. 3. Regression analysis for North America relating December–February snow cover to December–February temperature.

American data. Although the correlations for the Eurasian data are statistically significant, this does not necessarily imply that they are meaningful. However, it should be pointed out that though the correlations are not very strong, the data sets include a fairly wide range of temperature and snow cover conditions even though the period of study covers only 13 years. In addition, it should be noted that because a statistically significant relationship exists between Eurasian snow cover and the temperature of the continental interior, it cannot be inferred that a similar relationship exists for other regions of Eurasia. The temperature of the continental interior is only used as a simple indicator of the average temperature of the continent and is not intended to reflect the temperature conditions experienced in other areas of Eurasia.

When the winter snow cover (December–February) was plotted against winter temperatures, the correlation for Eurasia was −0.34 compared to −0.68 for North America (Table 3). Thus, for Eurasia the amount of variance in the winter temperature explained by the winter snow cover was much less than that explained by the snow cover in autumn. However, for North America the reverse is true; 46% of the variance in the winter temperature was explained by the winter snow cover as compared to only 4% by the autumn (September–November) snow cover (Fig. 3). The North American data was significant at the 95% level.

4. Discussion

The question arises as to why the relationship between the autumn snow cover and the ensuing winter temperature is much better for Eurasia than for North America, and conversely, why the winter snow cover is better related to the winter temperatures in North America than in Eurasia. It appears that the answer to this has to do with continentality, which is the degree of influence land has on climate. Using formulas based on the mean annual temperature range, Conrad (1946) and Ivanov (1959) among others, have demonstrated that Eurasia has a greater continentality than North America. Eurasia is more than twice the size of North America and is by far the largest continent on earth, and its enormous land mass significantly effects if climate.

For both Eurasia and North America the principal sources of cold air are the continental anticyclones of Siberia and northern Canada, respectively. Snow cover in the source regions leads to intense surface cooling with subsidence and the formulation of a low-level inversion. Because Eurasia has more of its surface area in northern latitudes than does North America, its snow cover is more extensive (Fig. 4), and as a result, the anticyclone found over Siberia is more pronounced and persistent than the corresponding high over northern Canada which is far less regular and is comparatively a rather weak and unstable feature (Lockwood, 1974).

In Eurasia, during the early autumn, cold air intrusions moving down from the Arctic bring about widespread cooling into central Asia. Generally by early October freezing temperatures are present over much of Siberia and a cold wave is gradually progressing from northeastern to southwestern Siberia (Lydolph, 1977). From Fig. 5 it can be seen that the

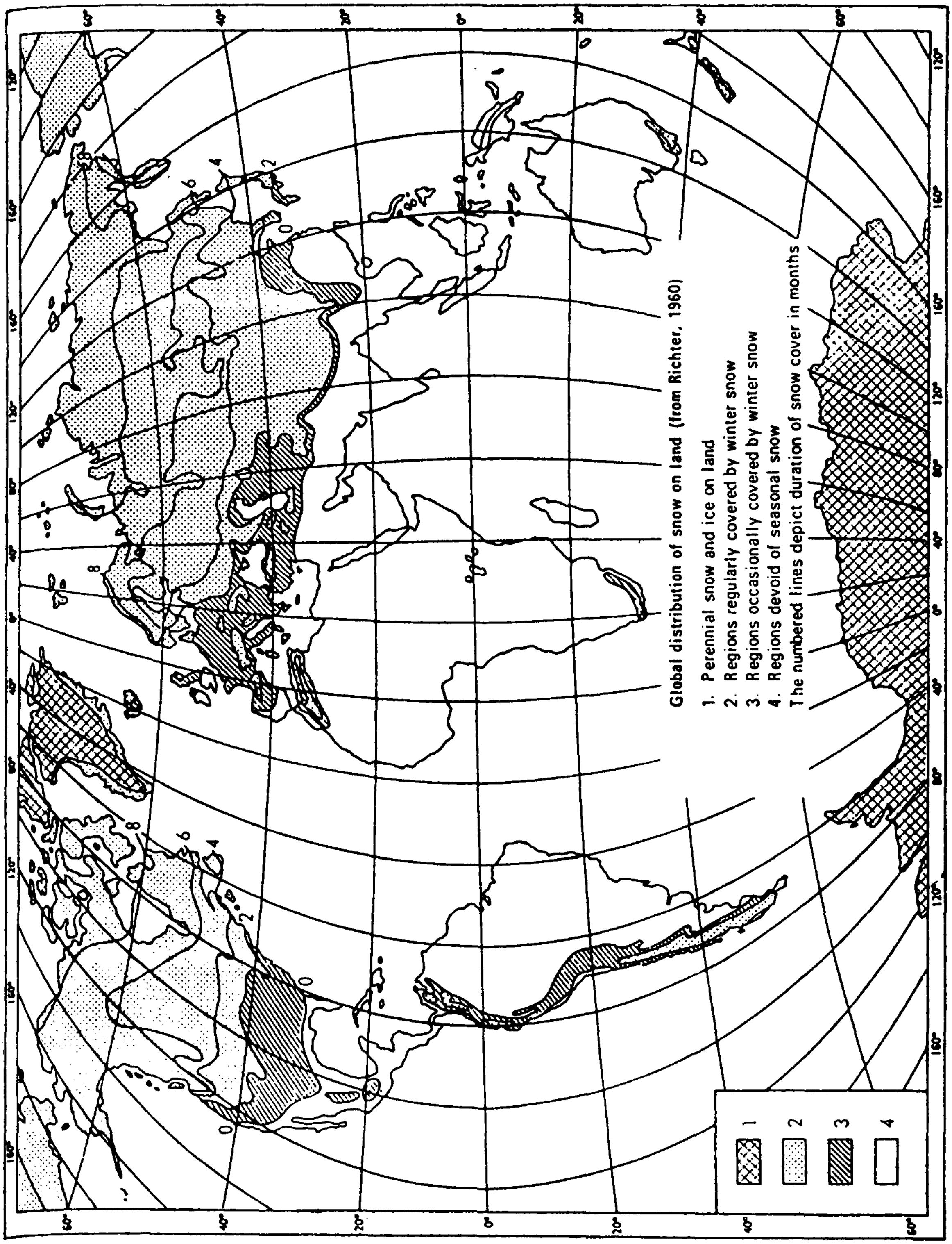

FIG. 4. Map showing global distribution of snow on land (WMO, 1975).

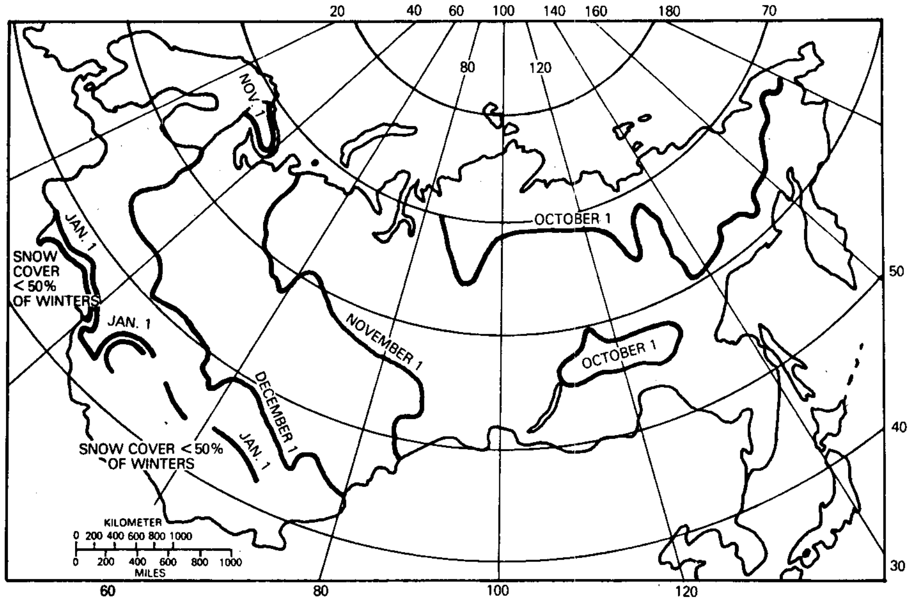

FIG. 5. Mean date of establishment of snow cover in the USSR (Lydolph, 1977).

snow cover becomes first established in north-central and northeastern Siberia. A shallow layer of cold air forms above the snow surface in response to radiative losses resulting from the increase in albedo of the expanding snow cover. By the middle of October the Asiatic high has already become evident. If the snow cover forms early and becomes deep and extensive, then the air above the snowpack is likely to be colder than if the snow cover is late forming and does not cover as extensive an area. The refrigerated air overlying the snowpack is transported southward during the late fall and winter cooling much of the continent. The degree of cooling, at least in the interior regions, seems to be associated with the snow cover conditions of the preceding autumn. The snow cover in October seems to be particularly important in explaining the amount of variance in winter temperature for Eurasia. Perhaps this is because the snow cover area increases much more during October than it does for any other month (Fig. 5).

By November, the Siberian or Asiatic high has become well developed as a result of the extreme surface cooling and the constant feeding of fresh Arctic air into central Asia (Lydolph, 1977). This high is large enough to effectively prevent the incursion of maritime air or air from other source regions into the continental interior. In addition, numerous mountain ranges hinder advancing air masses from the south and west. By December the snow-covered area has expanded well into the southern USSR. Because of the strength and constancy of the Asiatic high, even during relatively mild winters, temperatures in the interior regions are rarely above freezing and so there is very little melting of the snowpack. In fact, the location of the snowline during the winter months in central Asia may be more of a result of moisture availability than of temperature. Year-to-year variations in the winter temperature are due not as much to the winter snow cover as they are to other factors such as the variability of the large scale circulation. Thus, the correlation between winter snow cover and winter temperature in the interior of Eurasia is poor.

In North America usually by the middle of October the snow cover has become established throughout most of Alaska and northern Canada (Potter, 1965). The greater snow cover in September for North America (Table 1) compared to Eurasia (Table 2) is due to permanent snow fields in Greenland and the Canadian Archipelago. As autumn progresses, temperatures in the Arctic regions fall rapidly with the decreasing amount and intensity of insolation, and the snow cover continues to expand southward (Fig. 6). Anticyclones increasingly develop in the Arctic air masses over the interior of Canada and sometimes they intensify to control the weather over the greater part of the continent. However, maritime air mass systems from the west (Pacific Ocean) periodically penetrate into the interior of North America during the fall and winter. Contrasts between the cold Arctic air and the milder air from other source areas results in large temperature variations which show very little dependence on the snow cover extent of the preceding autumn.

The snow extent during the winter months in the interior of North America usually reaches ~40° north latitude. However, in some winters the snowline may be positioned near the Canadian border (49° north) (Fig. 1), whereas in other years the snowline

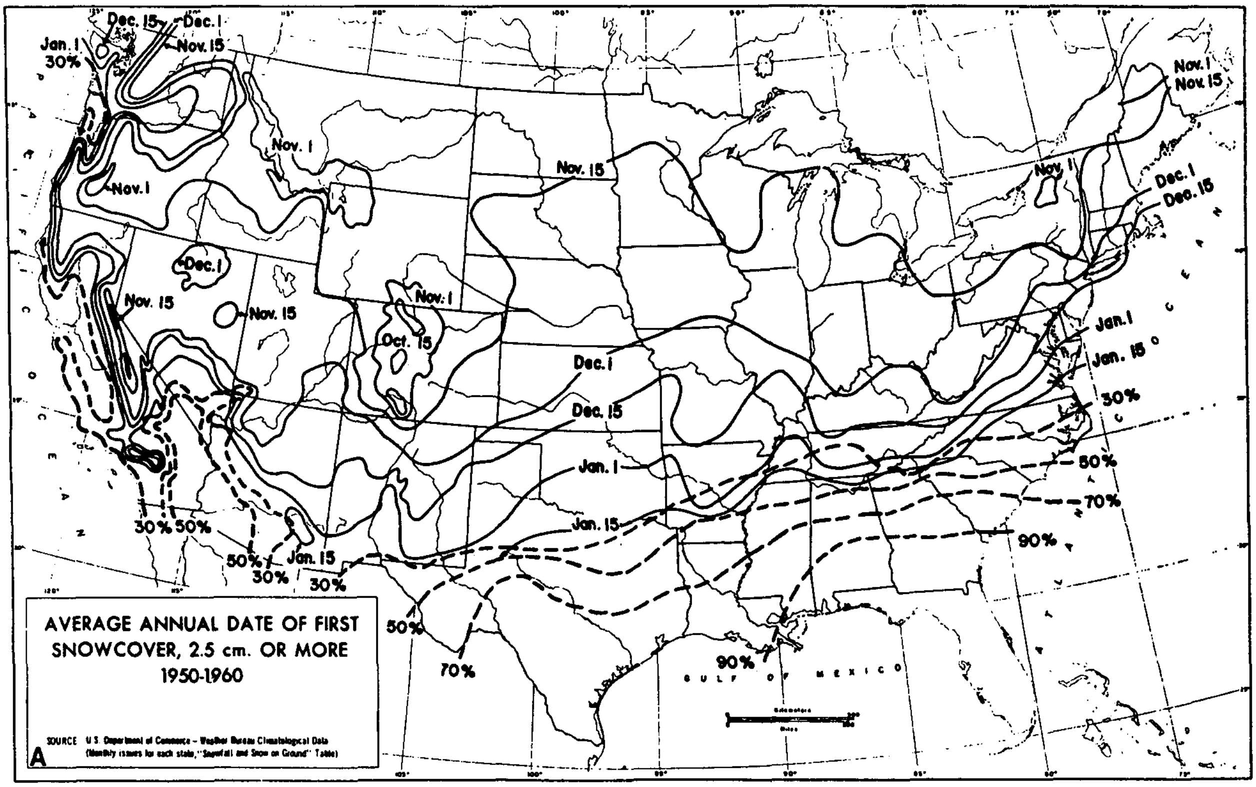

FIG. 6. Mean date of first snow cover (2.5 cm or more) in the United States.

may be located as far south as Oklahoma and Arkansas (33° north) (Fig. 7). It appears that when the snow-covered area in winter is extensive, the North American high is fairly strong, and consequently intrusions by air masses from other source areas are less likely to occur. Thus, temperatures in the interior will be cold. On the other hand, when the snow cover is not very extensive, the North American high seems to be weak or non existent and milder air from other source areas is more apt to make its way into the center of the continent. Hence temperatures in the interior will be rather mild. Since the mean winter snowline in North America lies closer to the continental interior than in Eurasia, the wintertime snow–temperature relationsip is better for North America than for Eurasia. While fluctuations of both snow cover and surface temperature can be viewed as consequences of the variable large scale circulation, part of the variance in winter temperatures unexplained by the circulation can be attributed to the winter snow cover conditions (Walsh *et al.,* 1982).

5. Summary and conclusions

In this study an attempt was made to see if there is a relationship between autumn snow cover in North America and Eurasia, and the ensuing winter temperature as measured at stations near the geographic centers of their respective continents. Temperatures from these stations were used as a simple indicator to approximate the average winter temperature for North America and Eurasia.

It was found that the regression correlations were much better for Eurasia than for North America. For Eurasia the r^2 values showed that as much as 52% of the variance in the winter (December–February) temperature could be explained by the snow cover extent in autumn, as compared to only 12% for North America. Using the temperature of the coldest winter month (January), instead of the December–February average, to plot against snow cover, did not improve the correlations. For the Eurasian data most of the correlations obtained by relating snow cover to temperature were significant at the 95% level. Given the state-of-the-art of long-range forecasting, a variance of 52% at a lag of one season is noteworthy.

When winter snow cover was correlated with winter temperature, it was found that the relationship was better for North America than for Eurasia. As much as 46% of the variance in the winter temperature was explained by the winter snow cover in North America compared to only 12% in Eurasia. The North American data was found to be significant at the 95% level.

It appears that differences between snow cover and temperature relationships in North America and Eu-

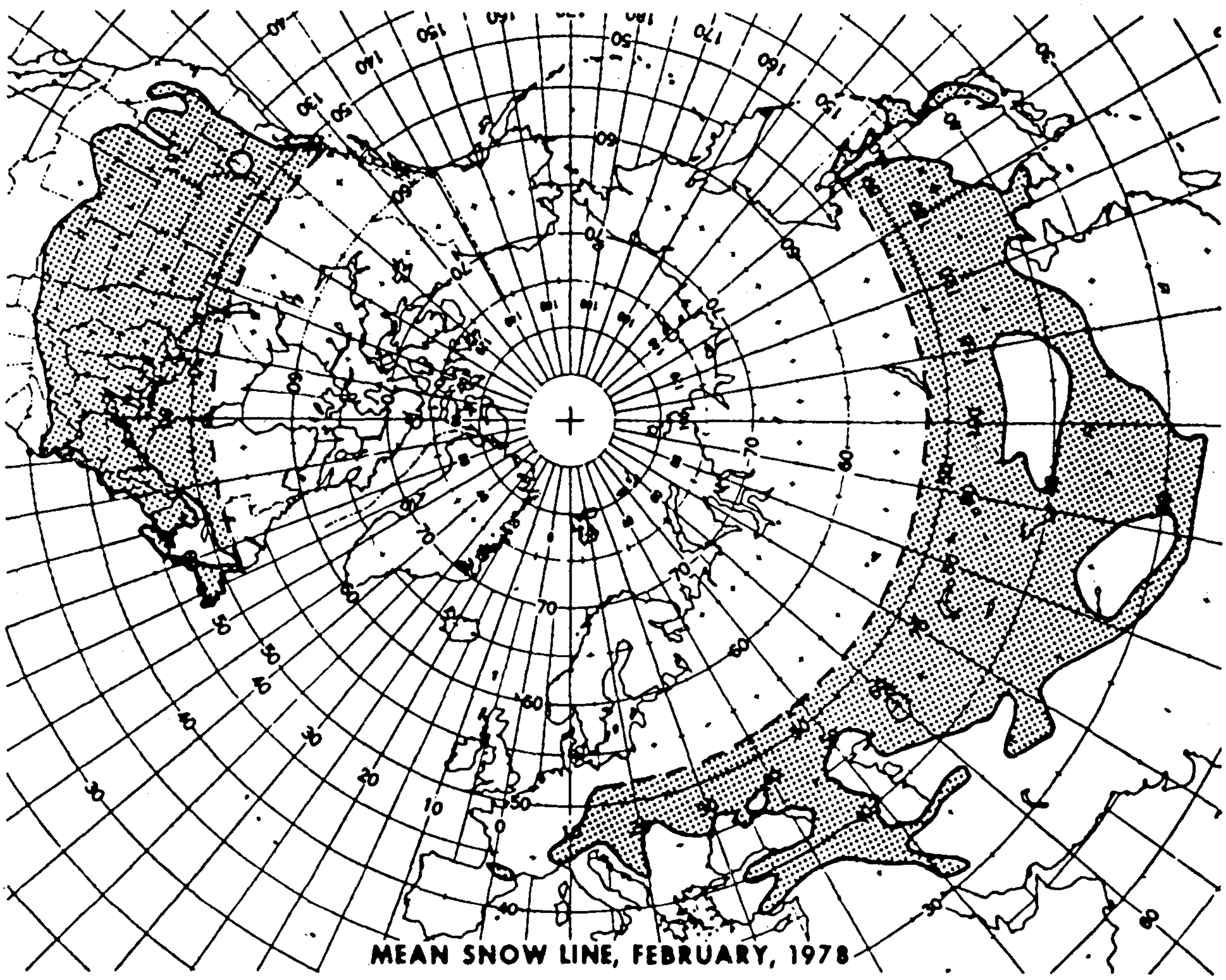

FIG. 7. Mean snowline in the Northern Hemisphere during February 1978.

rasia primarily have to do with differences in continentality. Because Eurasia is more than twice the size of North America and has more of its surface area in higher latitudes, its snow cover is more extensive, and as a result, the anticyclone over Eurasia is more pronounced and persistent than the corresponding high over North America. Once established, usually by November, the large Asiatic high continuously pumps cold air into the interior of the continent and prevents the intrusion of air masses from other source areas. In North America the anticyclone is not nearly as dominating as the Asiatic high.

The extent of the snow cover in Eurasia during the autumn seems to influence how cold the air will become and how far into the interior of the continent the air will penetrate during the ensuing winter. However, since during the winter months, the interior of Eurasia is nearly always snow covered, the winter temperatures are not well correlated with the winter snow cover extent. In North America due to the greater frequency of air mass intrusions into the continental interior, winter temperatures show very little dependence on the extent of the autumn snow cover. But because the mean winter snowline in North America lies closer to the continental interior than in Eurasia, temperatures are more responsive to snow cover variations.

The snow and ice cover in the Northern Hemisphere typically increases by ~40 million km^2 between September and December (Kukla and Robinson, 1981). Such a dramatic increase is bound to have a considerable impact on the earth's climate system. Changes in snow cover are accompanied by changes in the surface heat budget owing to the high albedo, the high emissivity and the low thermal conductivity of snow. Although it seems unlikely that the snow cover, as measured during the autumn months, can be used to reliably forecast the winter temperature in the continental interior, it has been demonstrated in this study that the snow cover extent can be statistically significant in explaining variations in temperature. Perhaps in future investigations techniques such as hindcasting can be tested to see if the inclusion of snow cover data increases the accuracy of forecast equations. The World Meteorological Organization has recommended that sensitivity studies be continued using general circulation models that give special attention to possible feedback mechanisms such as between snow cover and temperature. Satellite snow cover data of the Northern Hemisphere from 1966–81 has now been digitized by NOAA (Dewey and Heim, 1981), and Walsh *et al.* (1982) have recently digitized the snow cover data in the United States for the period from 1948–81 using data from surface stations. Because there are many types of climatological products which can be derived from these snow cover archives, a greater knowledge of the role snow cover plays in understanding climatic variability should result.

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