Snow Cover and Atmospheric Variability

John E. Walsh

Changes in the snow covering the earth's surface affect both daily weather and long-term climate

The largest changes that occur in the earth's surface over periods of several days to several months result from variations in snow and ice cover. Snow is one of the most noticeable elements of the weather experienced by the inhabitants of middle and high latitudes. For the meteorologist, it is a symbol of the scientific challenges posed by large-scale atmospheric variability. Snow's unique physical properties make it a potentially significant factor not only in day-to-day changes in the weather, but also in longer-term climatic variability.

The distribution of snow cover is largely a consequence of the pattern of atmospheric circulation, which favors the development of low-pressure systems and precipitation in certain regions. However, the pattern of circulation is itself determined by the distribution of diabatic heating—radiation, conduction, convection, and latent heating (the heat used in the evaporation of water and subsequently released during condensation). There are several ways in which snow cover modifies the exchange of energy between the surface and the atmosphere, and hence the distribution of diabatic heating. First, the albedo, or reflectivity, of fresh snow is 0.80–0.85 for sunlight, whereas the albedo of bare land or an ice-free ocean is typically between 0.05 and 0.30. Snow cover can therefore reduce the solar energy available to the surface and lower atmosphere by more than 50%. The actual magnitude of the reduction will depend on the age and depth of the snow, the vegetative cover, cloudiness, and the seasonally varying intensity of the sunlight. If this energy deficit is assumed to be distributed through the lowest 2 km of the atmosphere, it can be equivalent to a cooling of 3–7° C in middle latitudes under clear skies (Namias 1960).

Fresh snow also has an extremely low thermal conductivity, which makes it a highly effective insulator. Soil may remain unfrozen for several weeks beneath a snow cover of 20–30 cm, even when air temperatures are 10–20° C below freezing (Kukla 1981). Snow is a very effective radiator of heat in the wavelengths of terrestrial radiation, which means that it readily gives off long-wave radiation absorbed from the atmosphere. Finally, melting snow serves as an effective sink of latent heat for the atmosphere. Unusually heavy accumulations of snow in late winter or early spring will therefore delay the normal seasonal changes in air temperature. The net result of all these factors is that the air above the snow cover is generally cold and incapable of holding large amounts of moisture.

Surface variables such as snow cover and the ocean's surface temperature change relatively slowly compared to the atmospheric variables of pressure and wind velocity, which is why changes in the surface properties may be useful in long-range weather forecasting. If anomalous sources and sinks of heat evolve slowly enough, they may contribute to the predictability of atmospheric variability over periods of weeks or longer. These atmospheric fluctuations should be most detectable in the general vicinity of the surface anomaly.

Recent theoretical studies have shown that the effects of anomalous heat sources may be propagated to distant regions by the internal dynamics of the atmosphere (Hoskins and Karoly 1981; Webster 1982). The extent to which a surface anomaly gives rise to such long-distance propagation, historically referred to as teleconnections, depends on several factors: the extent, magnitude, and persistence of the anomaly, and the basic state of the overlying atmosphere, which includes the vertical distribution of wind and temperature and which can strongly influence the atmosphere's susceptibility to teleconnections. Since the basic state of the atmosphere varies seasonally and regionally, so do the remote effects of surface anomalies. The atmosphere's basic state appears to be most favorable for teleconnections during winter if the anomalies occur in low latitudes, and in the summer if the anomalies are in middle and high latitudes. Therefore, the atmosphere is not ideally suited for large-scale propagation when the snow cover is most extensive.

This article surveys the associations between snow cover and atmospheric variables, using results from observations as well as models in order to assess the interactions quantitatively. Of particular interest are the implications for improved prediction of both snow cover and the associated atmospheric variations. In view of the dependence of these interactions on the scale of the snow cover, the survey proceeds from short periods of about a day to the longer periods generally associated with climate.

The discussion below is limited to snow cover over land. The subject of variable sea-ice cover, which dramatically affects the balance of energy on the ocean's surface, has been reviewed by Untersteiner (1975) and Allison (1982) and will not be addressed here.

John E. Walsh, Associate Professor of Meteorology at the University of Illinois, received a B.A. in mathematics from Dartmouth College and a Ph.D. in meteorology from MIT. He has been a visiting scientist at the National Center for Atmospheric Research on several occasions since his arrival at the University of Illinois in 1974. His research has focused on sea ice, snow cover, and other surface variables in the context of short-term climatic variability. Address: Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801.

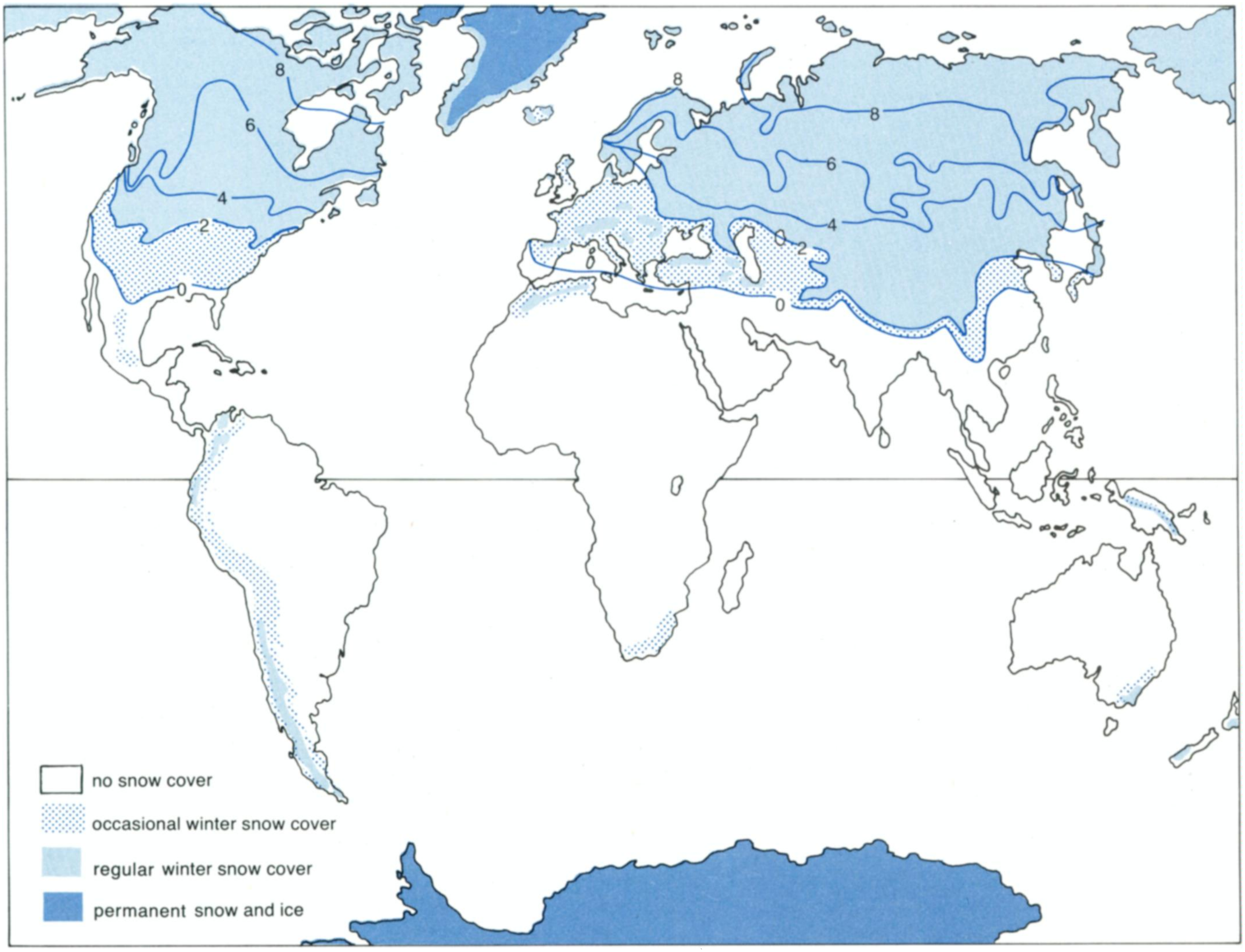

Figure 1. A large part of the Northern Hemisphere is covered by snow during part of the year, as the extent of snow varies from a maximum in February to a minimum in September. The numbered lines indicate the normal number of months that the snow cover lasts; the dotted areas represent the wintertime marginal snow zone, in which the boundary of the snow cover fluctuates from December to March. (After Richter 1960; Untersteiner 1975.)

Snow cover in the present climate

A striking feature of the present-day distribution of snow cover over land is the virtual absence of seasonal snow in the Southern Hemisphere, where the only large area of land at latitudes in which snow cover can easily accumulate is the glaciated Antarctic continent (Fig. 1). The following discussion of interactions between snow and the atmosphere is therefore limited almost exclusively to the Northern Hemisphere.

Although the average snow-covered area of Eurasia is nearly twice as large as that of North America during winter, year-to-year differences in the southward extent of snow on the two continents are comparable. Figure 2 illustrates the year-to-year variability of the snow cover of Eurasia and the United States in recent decades. Despite a series of extreme values for both regions in the late 1970s, the relatively short length of time for which large-scale data are available does not permit the detection of any trend.

On the basis of data for selected locations in western Europe, Lamb (1977) noted an increase in the amount of snow cover from the late 1800s to the mid-1900s, with a return to smaller amounts during the early 1970s. Lamb also reported a tendency for snows in Japan to occur earlier in the winter during the mid-1900s than during the late 1800s. Although changes such as these may indeed occur in specific locations, the data on which Figure 2 is based indicate that large fluctuations in opposite directions can take place concurrently in different portions of the hemisphere.

The variations implicit in Figures 1 and 2, in conjunction with snow's unique physical properties, provide the basis for suspected associations between snow cover and atmospheric variability. Even during the winter, the marginal snow zone—the area in which the boundary of the snow cover fluctuates—is generally south of the zone of 24-hour darkness. Snow-induced modifications of the amount of solar energy absorbed by the land are therefore possible year-round, although the incoming energy will be weak in any case during the winter months. For the sake of perspective, we note that the area of the ocean's surface subject to temperature anomalies is considerably greater than the area of the marginal snow zone. Since fluctuations in the ocean's temperature normally extend tens of meters below the

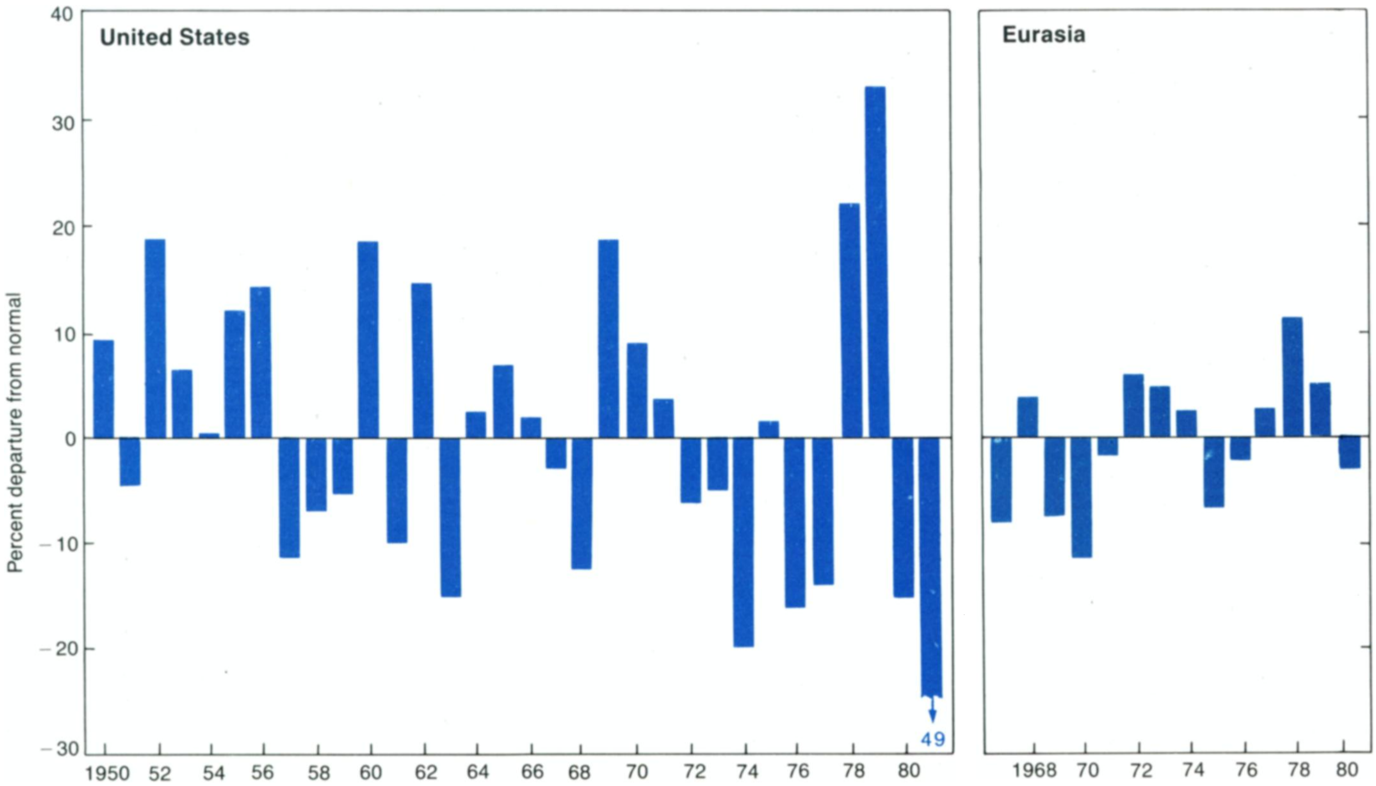

Figure 2. The amount of land covered by at least 2.5 cm of snow varies considerably from one year to the next. Departures from the normal winter average have recently ranged from an increase of 33% to a decrease of 49% in the United States, excluding Alaska, and from a gain of approximately 12% to a loss of 10% in Eurasia. The percentages of change are smaller in Eurasia because of the larger normal snow cover there than in North America. The dates given are the years in which the winters, lasting from December to February, ended. (Data from Walsh et al. 1982; Dewey and Heim 1982.)

surface, they represent substantial thermal reservoirs with potential atmospheric associations even stronger than those of snow cover.

Local atmospheric associations

Local associations between snow and atmospheric variables are perhaps the most obvious. For example, the type of precipitation depends on the ambient air temperature. Although snow can fall to the surface when air temperatures there exceed 0° C, the temperature is usually lower aloft. In fact, the position of the 0° C isotherm at 1 km is generally a close approximation to the line at which rain changes to snow in cyclones in the middle latitudes.

After snow has covered the land, its local effects on the atmosphere are readily apparent. A striking example of the lowering of maximum daily temperatures by snow is shown in Figure 3, which compares the depth of snow reported in the central United States with the subsequent errors in forecasts of maximum temperature produced by a numerical procedure that does not consider snow cover. Because Figure 3 depicts a situation late in the winter, the solar radiation subject to surface reflection is relatively high. However, even earlier in the winter, the average temperatures at several North Dakota cities have been found to be approximately 10° C colder on days with snow than on days with no snow (Kukla 1981). Although wind direction, upstream temperatures, and other factors are undoubtedly responsible for substantial portions of the 10° C difference, the association between snow cover and air temperature is strong and significant.

Analyses of the rates at which relatively warm, moist air is cooled as it flows over snow indicate that, with air flowing northward over snow ~15 cm deep, the loss of heat by conduction to the surface can reduce the temperature by 4–5° C per day (Treidl 1970). The impact of snow cover on temperature is therefore not limited solely to radiative effects.

Since monthly data are essentially averages of daily values, it is not surprising that anomalies of monthly snow depth correlate negatively with monthly air temperature at the same location (Wagner 1973). When monthly temperatures at weather stations in the United States are grouped on the basis of concurrent snow cover, temperatures during the 10% of the winter months with the most extensive snow cover are lower by 3–6° C than those during the corresponding months with the least snow. Differences of this magnitude are found along a broad east-west band extending ~500 km to either side of the normal boundary of the snow cover (Walsh et al. 1982). During the winter, the largest differences, which in December occur in the East, move toward the continental interior, where the warming during the late winter and early spring months without snow cover is normally most rapid. Maritime influences are relatively weak in the continental interior, so it is not surprising that surface variables such as snow cover become progressively more important as solar radiation increases during the late winter.

As noted earlier, however, temperature differences such as these cannot be attributed entirely to snow cover. Snowfall and temperature anomalies may both be consequences of the pattern of atmospheric circulation. For example, temperatures in Florida are generally several degrees centigrade below normal during months with heavy snow in the eastern United States, even though the snow rarely reaches Florida. These lower temperatures occur because the circulation regimes that favor heavy snow in the East also drive cold air south to Florida. The normal warming of the polar air masses is reduced by an extensive snow cover. Circulation patterns relevant to snow cover are discussed in the following section.

One effect of the reduced temperatures caused by abnormally extensive snow cover is a delay in the seasonal warming of the air. In western Europe, the temperature of the air at the surface begins to increase in February if the ground is free of snow, but not until several weeks later if snow is present (Lamb 1972). In their search for seasonal predictability, Soviet investigators found that the surface albedo of early spring is significantly correlated with the temperatures of late spring and early summer in the northern USSR (Toomig 1981). The albedo accounts for 15–25% of these subsequent variations in temperature.

Large-scale associations

A discussion of interactions between the snow cover and the atmospheric circulation requires the consideration of large-scale patterns of atmospheric variables. A commonly used representation of the large-scale circulation is a chart depicting the elevation of a particular pressure above sea level. Because the horizontal gradients of the height of a particular pressure "surface" are proportional to horizontal pressure gradients at that height, a map of the height of a pressure surface in the upper atmosphere effectively shows the regions of low and high pressure aloft. Upper-air winds closely parallel the contours of the pressure surface at their level, and the wind speeds are proportional to the density of the contours.

Since approximately half of the troposphere's mass is below 700 millibars (mb) of pressure, diagnostic studies of the tropospheric circulation are frequently based on the horizontal gradients of the height of 700 mb. Figure 4 shows the normal winter height of 700 mb over the Northern Hemisphere and its correlations with snow cover in the United States. Because the wavelike pattern apparent in the normal distribution of 700 mb heights is also apparent in the correlation fields derived from anomalies in the heights and snow cover, changes in the large-scale pattern are evidently related to fluctuations in the snow cover. The three-part wavelike pattern apparent in the correlation fields is characteristic of the Pacific–North American teleconnection pattern, which has been shown both observationally and theoretically to be associated with anomalies in the temperature of the sea's surface in the equatorial Pacific Ocean (e.g., Horel and Wallace 1981). These anomalies, in turn, are part of the so-called "Southern Oscillation," which is currently under intensive investigation as a potential predictor of short-term climatic fluctuations over North America.

When the correlation fields of Figure 4 are recomputed using snow cover of one month and 700 mb heights of the following month, the patterns are considerably weaker. The correlation fields therefore imply

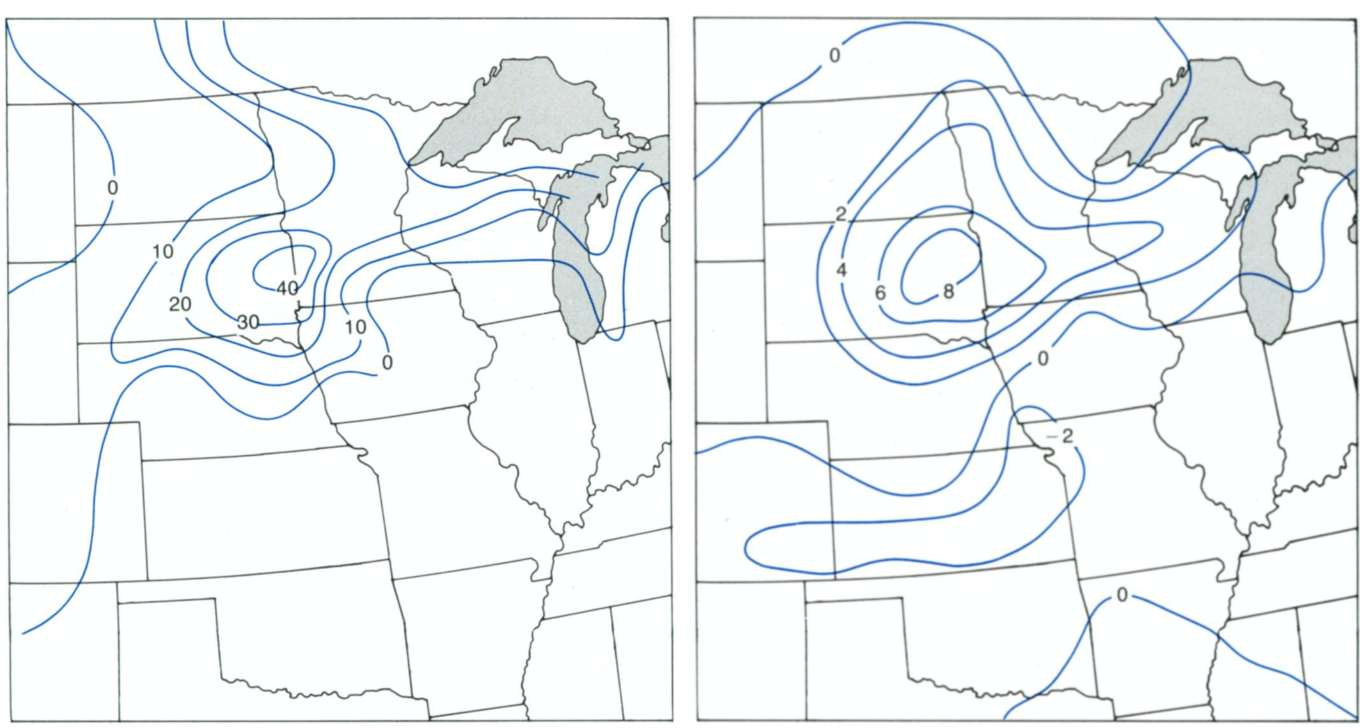

Figure 3. Snow cover can have a profound effect on air temperatures near the surface. The varying depth of the midwestern snow cover on 5 March 1977 led to corresponding errors of 2-8° C in forecasts of the maximum daily temperature for the next five days, which were produced by a statistical model that does not take snow cover into account. Forecasts generated by this type of model are typically in error by only 1-2° C. (After Dewey 1977.)

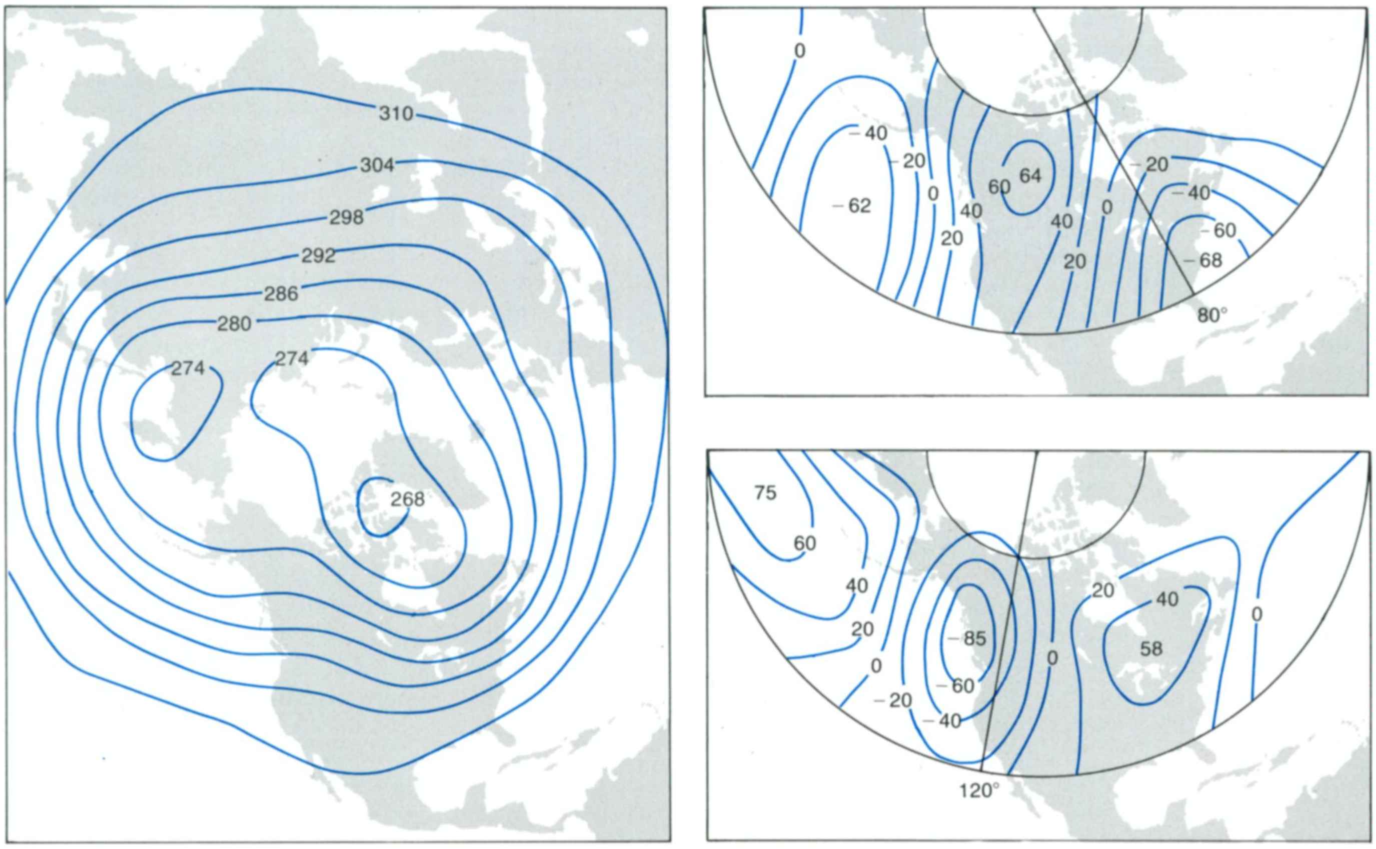

Figure 4. Large-scale atmospheric circulation, indicated by the average winter heights in decameters of 700 mb (*left*), affects the extent of the snow cover. In colder regions the relatively rapid vertical decrease in pressure produces a "trough" of 700 mb heights and the snow cover is generally above average; it is usually below average in the warmer regions, where there is a "ridge" of 700 mb heights. The wavelike pattern in the heights of 700 mb also occurs in correlations of the heights with winter snow cover in the eastern (*top right*) and western (*bottom right*) United States, at 80° and 120° of longitude, respectively; the snow cover correlates almost as strongly with 700 mb heights over the North Pacific Ocean as it does with local heights. Local anomalies of the snow cover and of the 700 mb heights tend to be of opposite sign. (After Walsh et al. 1982.)

that variable snow cover is largely a response to, rather than a cause of, changes in the pattern of large-scale circulation. However, since the results presented earlier indicated that snow cover can have a substantial local impact on atmospheric variables, the intriguing question remains: Does snow cover have significant effects on the large-scale circulation?

The answer to this question is complicated by the host of other factors that affect the circulation. Nevertheless, observational data suggest that, if the snow cover is abnormally large and persistent, it does play a role in the large-scale climate. These encouraging findings were presented several decades ago by Lamb and Namias, who pioneered the study of the short-term climatic fluctuations. Lamb (1955) compiled statistics based on European snow cover and the depth, or thickness, of the atmospheric layer between 1,000 mb and 500 mb. The thickness is directly proportional to the mean temperature of the layer. Lamb's analysis showed that the thickness is significantly smaller over snow-covered surfaces. More important, when layers with very large thicknesses pass over large areas of snow cover, the thicknesses decrease as the air becomes cooler. It follows that an extensive snow cover can contribute to the maintenance of a trough of cold air in the troposphere by affecting the horizontal temperature gradients at low levels in the atmosphere, which in turn modifies the distribution of pressures and winds aloft. The cold trough then contributes to the persistence of the snow cover. According to Lamb's results, this large-scale feedback occurs when the dimensions of the snow-covered area are $\gtrsim$2,500 km, unless the wind speeds exceed 90 km/hr or unless the air is descending at an unusually rapid rate.

Namias (1960, 1962) performed a diagnostic analysis of the severe late winter of 1960, when the snow line was 5–10° south of its normal position in the eastern and central United States. Forecasts based only on the pressures and winds overestimated the surface air temperatures by 4–5° C in the south-central part of the country during February and March 1960. The extreme cold was therefore due not only to southward movement of the air but also to the snow itself, since the abnormal snow cover prevented the normal warming of polar air masses. The thermal contrasts between these polar air masses and the air just above the warm coastal waters led to strong and rapidly developing cyclones, which reinforced the deep cold trough over eastern North America. Namias (1981) suggested a similar feedback involving extensive North American snow cover during the winter of 1976–77.

Extensive snow and extreme cold over eastern North America have also been linked to anomalies in the winter climatic regime of Greenland and northwestern Europe (Dickson and Namias 1976). The enhancement and southward displacement of cyclones on the East

Coast of the United States lead to a reduction of cyclonic activity near Iceland and Greenland. This weakening of low-pressure systems near Iceland reduces the northward flow of air in the eastern North Atlantic, thereby increasing the frequency of cold outbreaks from the polar region over northwestern Europe. The frequent recurrence of this abnormal winter regime during the 1960s may have contributed to the relatively extensive European snow cover during that decade.

The tendency for snow cover to reinforce troughs of cold air in the upper atmosphere during other seasons has been suggested by Lamb (1972), who argued that the exceptionally cold summer of 1968 in northeastern Europe and northwestern Siberia was attributable in part to the previous winter's extensive snow cover. Because the snow did not retreat until June and July, the ground remained cold and saturated, which favored the persistence of a trough. The attendant cloudiness and development of cyclones led to frequent rains and occasional snowfall throughout the summer over the northern USSR. Persistent snow may have played a similar role in the unusually cold North American summers of the 1930s (Wahl 1968).

Foster and his colleagues (1983) have recently reported a surprisingly high correlation (r = 0.72) between Eurasian snow cover during October and November and air temperatures during the subsequent winter at several locations in the central USSR. The authors suggested that when the Asian anticyclone develops early, which is more likely when there is extensive snow cover in the autumn, it is unusually strong and cold. Since this anticyclone dominates the continental interior during winter, much more so than does its North American counterpart, much of Eurasia is colder than normal when the anticyclone is well developed.

The studies cited above have addressed the climatic implications of unusually extensive snow cover; on the other hand, Namias (1964) has suggested that a lack of snow may contribute to recurrent "blocking" in regions such as Scandinavia. Blocking refers to the persistence of closed upper-air systems that are cut off from the main patterns of eastward flow. If the absence of snow permits a more rapid springtime warming, then the greater thermal contrast of the land with surrounding waters should favor the development of a ridge in the upper atmosphere, possibly perpetuating a blocking regime over several seasons. This type of reasoning is similar to that invoked to explain the link between the winter snow cover over Eurasia and the intensity of the Indian summer monsoon. Postulated long ago by Blanford (1884) and Walker (1910), this link has been substantiated in recent years with the aid of satellite-derived measurements of Himalayan snow cover (Hahn and Shukla 1976; Dey and Branu Kumar 1983). The inverse relation between snow cover and the intensity of the monsoon, shown in Figure 5, is consistent with the argument that an extensive snow cover contributes to lower springtime air temperatures and high pressure at sea level over southern Asia. The higher pressure opposes the normal seasonal tendency of the winds to converge into a monsoon, which is responsible for the summer rainfall.

The examples discussed above are both intriguing and suggestive with regard to the weekly or seasonal climatic effects of snow cover. It should be noted, however, that the claims about the impact of the snow cover are based on a combination of selected cases, small samples of data, and varying amounts of speculation. Limitations such as these may be inevitable when the associations vary seasonally and regionally, and especially when snow cover is only one of many factors affecting the distribution of diabatic heating. Models of general atmospheric circulation, which have thus far received little use in studies of snow cover, are only now becoming sophisticated enough to allow the controlled experiments needed to confirm the existence of these associations and to clarify the physical mechanisms responsible for them.

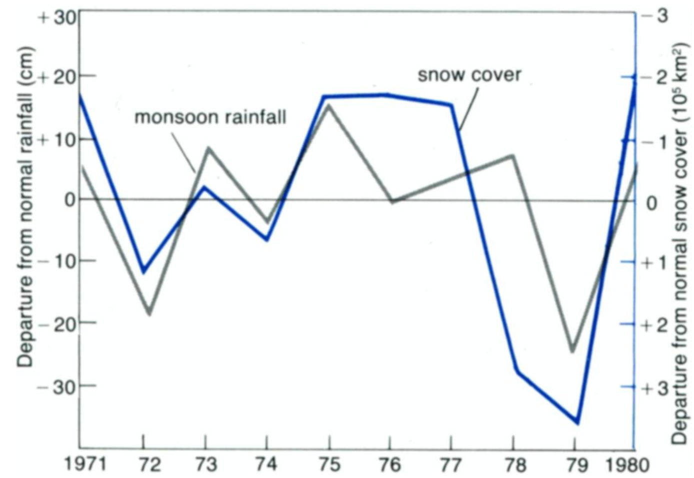

Figure 5. The Indian monsoon rainfall from June to September tends to vary inversely with the Himalayan snow cover of the preceding December to March. The diagram is scaled so that the monsoon rainfall increases upward, while Himalayan winter snowfall increases downward. (After Dey and Branu Kumar 1983.)

Long-term climatic associations

Although the role of snow cover in short-term climatic variability may be limited by the range of its annual fluctuations, it is reasonable to assume that the climatic importance of snow cover increases as its extent changes systematically over longer periods of time. The earth's distribution of snow and ice as well as its other climatic features are known to have been quite different in past centuries. We now extend the discussion of interactions between the snow cover and the atmosphere by considering the role of snow cover in the inception of glaciation, and the possible enhancement by snow cover of a climatic warming induced by greater levels of carbon dioxide in the atmosphere.

The massive ice sheets that have periodically covered much of North America and northern Europe in the past million years are believed to have originated in northeastern Canada and Scandinavia, respectively. The periodicity of the ice ages has recently been linked rather convincingly to changes in the earth's orbital parameters, which in turn determine the amount and distribution of solar radiation reaching the earth (Hays et al. 1976). Other scenarios have been proposed with varying degrees of speculation and controversy. Flohn (1974), for example, argued that when the Antarctic ice shelves expand rapidly offshore, the waters of the western North

Atlantic become cooler and a trough forms over eastern North America. On the other hand, Brinkmann and Barry (1972) and Adam (1973) suggested that the initial formation of snow cover in northeastern Canada is largely responsible for the development of this trough.

Regardless of the immediate cause of its development, a continental trough is a likely key to the beginning of glaciation for two reasons. First, cyclonic development along the eastward flank of an upper-level trough will provide a source of moisture for a developing ice sheet. Second, the associated low-level flow of air will move cold air southward along the western flank of the trough so that existing snow is more likely to survive during the summer. The presence of snow cover in the summer should strongly enhance the feedback between the albedo and the temperature, thereby favoring the further expansion of the snow cover.

Interestingly, all scenarios for the development of ice sheets invoke this feedback. Results from climate models indicate that the effects of orbital variations are too small to account for the major glaciations unless the models include the enhancement of the albedo by the expanded snow cover (Williams 1978). Moreover, Williams's observational data for eastern Canada during 1967–75 show that extensive October snow cover is accompanied by decreases of ~3° C in the surface air temperature, decreases of 60 m in the height of the 500 mb pressure, and a doubling of precipitation in October. When combined with the temperature changes ascribed to the orbitally induced variations in the summer solar radiation, the associations derived from these October data are quite compatible with periodic glaciation of the eastern Canadian Arctic.

Additional evidence that snow cover had a role in the ice-age climate has been provided by a model of the global atmospheric circulation (Williams 1975). In a simulation of the climate of July with elevation, snow and ice cover, and surface temperature of the ocean corresponding to the conditions of the most recent glacial maximum of ~18,000 B.C., the upper-level circulation contained a relatively deep trough over eastern North America and a weaker trough over western Europe. A tendency for cyclones to move along the boundary of the North American snow cover was also evident. A parallel simulation with present-day surface elevations showed that the differences from the present circulation result primarily from changes in surface reflectivity, rather than from changes in elevation, which points quite convincingly to the effect of snow cover on the climate.

Considerable concern has been expressed in recent years about the possible climatic impact of increasing concentrations of carbon dioxide. Because it is not feasible to study the effects of different levels of carbon dioxide in the field or in the laboratory, numerical models have provided most of the estimates of the effects. The widely quoted results of Manabe and Stouffer (1980) are based on a pair of simulations with the present concentrations of carbon dioxide and with four times this concentration. Although in the latter case the global mean surface air temperature is approximately 4° C higher, there are significant seasonal and latitudinal variations in the warming. Of special interest here is the fact that the largest increase in temperature occurs in the high latitudes of the Northern Hemisphere, primarily because of the albedo-temperature feedback. The Southern Hemisphere experiences relatively little warming because of its small areas of snow-covered land and sea ice. The longitudinally averaged surface warming in the Northern Hemisphere exceeds 6° C at all latitudes above about 50° N, although a large portion of the albedo-temperature feedback occurs only in ocean areas where sea ice retreats. At high latitudes over the continents, the temperature rises by more than 8° C during the period from October to May, when the snow cover is relatively extensive in the simulation using the present level of carbon dioxide. In the summer, when there is little snow in either simulation, the continents in the high latitudes warm by much smaller amounts.

Like most model results, those of Manabe and Stouffer suffer from deficiencies in the model and corresponding errors or biases in the simulation of the present climate, particularly with regard to sea ice. Nevertheless, these results suggest that the climatic effect of increasing concentrations of carbon dioxide may be substantially enhanced by changes in the albedo of regions now covered by snow.

The results discussed in this paper show that the distribution of snow cover can be explained largely by the temperature distribution and the large-scale pattern of atmospheric circulation. Feedback of the snow cover to the atmosphere is less readily detectable amid the complex web of air-sea-land interactions. Nevertheless, the observational evidence suggests that snow cover contributes to atmospheric variability. As models of the air-sea-land system are refined over the next several decades, we should see considerable progress in the realistic modeling of snow cover. With the recent observational analyses and the imminent improvement of the models, our understanding of the climatic role of snow cover is advancing rapidly.

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"Geology to the left of us. Geology to the right of us. Wherever we look, geology. And *we* can get in on the ground floor."