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Increased Surface Albedo in the Northern Hemisphere

Did satellites warn of the weather troubles of 1972 and 1973?

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Snow and pack-ice cover in the northern hemisphere formed earlier in the year and covered a larger area in the past 3 years than it did 7 years ago, when systematic satellite mapping began. This shift, in all likelihood, has produced a significant change in the hemispheric heat balance. The difference was most pronounced in the fall and was especially large in 1971. The anomalous global weather patterns of 1972 and 1973 may be the result of these developments.

This is the main conclusion of our study of secular changes in snow and ice cover in the northern hemisphere. The data are from weekly maps from the National Oceanic and Atmospheric Administration (NOAA) based on photography from meteorological satellites (*1*). The charts show snow and ice fields remaining for at least 5 days.

The location and duration of snow and pack-ice fields constitute the most important seasonal variable in the earth's heat balance (*2*). Normally vegetated ground reflects only about 15 to 20 percent of insolation and calm ocean reflects 5 to 10 percent, but the snow-covered grasslands or pack ice reflect approximately 80 percent (*3*). The atmosphere is principally heated by the underlying surface; thus, the reflected light, escaping back to space instead of being transformed into heat, represents a deficit in the earth's energy balance. In addition to this, the pack ice cuts off, almost completely, the heat exchange between the warmer ocean and cooler air (*4*).

When melting into water, ice and snow consume almost 80 calories per gram. It is partly for this reason that the summer peak air temperatures in the northern mid-latitudes are delayed 6 weeks after the insolation peak. The high albedo (reflection) of clouds is often associated with warming of the lowermost troposphere because of the simultaneous greenhouse effect of the wet air, but the high albedo of snow and pack ice is invariably accompanied by strong radiative cooling (*5*).

Changes of Snow and Ice Cover

In 1968, the global minimum extent of snow and ice was about 38 $\times 10^6$ square kilometers (7.5 percent of the earth's surface) and was reached in August (Fig. 1). The maximum, 76×10^6 km^2 (15 percent of the globe's surface), was attained at the end of December 1968 and in the first days of January 1969.

Permanent ice covers 10×10^6 km^2 in the north and 14×10^6 km^2 in the south, while about 20×10^6 km^2 of pack ice in the south and 50×10^6 km^2 of snow and ice in the north have only seasonal duration (*6*). The seasonal variation is larger in the northern hemisphere because of the extensive continents supporting snow. Satellite-derived maps of the southern hemisphere, visually charted by Streten (*7*), and the measurements of Antarctic pack-ice fields in July and August made with the use of infrared imagery (*8*) were also used in the construction of Fig. 1.

Figure 2 shows the seasonal variation of snow and pack-ice cover in the northern hemisphere between 30 March 1967 and 1 November 1973 due to the normal annual cycle. The minimum coverage was repeatedly reached during the last week of August and the first week of September. Until 1971, and again in 1973, snow and pack ice covered 9.5×10^6 to 9.8×10^6 km^2; in 1972 the minimum coverage was 10.3×10^6 km^2. The summer pack-ice boundaries of 1973 are shown in Fig. 3, together with extensive areas of snow that, since 1971, have failed to melt in the Coast Mountains of British Columbia, and in the Asian mountain ranges of Tien-Shan, Pamir, Hindu Kush, and the Himalayas. The Arctic Ocean was more open this summer than during the previous 6 years.

From February through August the snow and ice fields repeatedly disintegrated. The process was very fast in April and May and slow from the end of June through July and August.

To facilitate comparisons of snow patterns in the northern hemisphere in different years, four snow cover (SC) seasons are recognized. The SC-summer is the part of the year when less than 15×10^6 km^2 of ground and ocean are covered by snow and ice. Correspondingly, SC-winter is the period when more than 55×10^6 km^2 are covered, while SC-spring and SC-fall are the intermediate intervals.

The combination of fall and winter could be conveniently labeled as the

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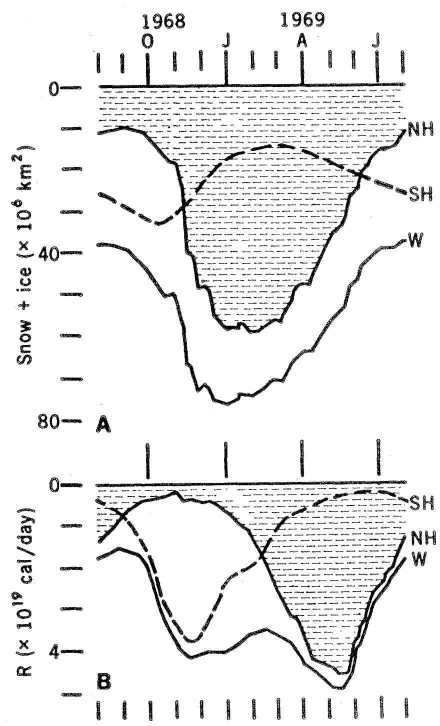
Fig. 1. (A) Area covered by snow and pack ice and (B) related reflection loss (R) from August 1968 to September 1969, based on 5-day minimum brightness composite images obtained from ESSA and Nimbus satellites. The index R shows the amount of radiation reflected in excess of that reflected by bare ground because of the presence of snow and ice. It refers to a simple model with a parameterized atmosphere and surface albedo. The time scale shows first day of each month. Abbreviations: *O*, October; *J*, January; *A*, April; *J*, July; *NH*, northern hemisphere; *SH*, southern hemisphere; *W*, world.



accumulation period and spring and summer as the melting period. This is not an accurate subdivision as the accretion of snow fields actually starts at the end of SC-summer and their disintegration starts at the end of SC-winter. Also, the extent of Arctic pack ice attains its minimum in October and its maximum in April, when the snow fields in the mid-latitudes have already been in retreat for several weeks.

As shown in Table 1, which refers to the last 7 years, SC-spring was, on the average, 7 weeks longer than SC-fall, whereas SC-summer and SC-winter had almost the same mean duration. The starting dates of the SC-seasons changed substantially from year to year. Especially interesting are the consecutively earlier starting dates of SC-fall and SC-winter from 1970 to 1972 and the striking difference in the starting date of SC-spring between 1970 and 1971.

Corresponding variations are reflected in the monthly means of snow and ice extent plotted in Fig. 4. There is a particularly large difference between the values for February, March, April, September, October, and November of 1970 and 1971. Also conspicuous is the gradual increase of snow and ice cover in October and November within the recorded period. In October 1972 snow and ice covered twice as much ground as in October 1968 (9). The variance in monthly means is largest in November and smallest in August.

Figure 5 shows the running annual means of snow and ice cover in the northern hemisphere plotted at the last day of the period represented. The mean annual coverage for the entire period was 34.9×10^6 km^2. This parameter increased by 12 percent—that is, from 32.9×10^6 to 36.9×10^6 km^2—during the single year 1971. Since then, it has fluctuated between 36.7×10^6 and 37.5×10^6, and was 36.7×10^6 km^2 on 1 November 1973. Thus, the period on our record could be divided into two sections, sharply differing in their patterns of seasonal distribution of snow and ice: before 1971 and after 1971.

Limited Precision of Data

The accuracy of the information presented here is affected by the variable quality of the basic data and by various approximations made in their analysis. The main sources of possible error are the following.

1) The snow and ice boundary maps are prepared from computerized digital products obtained by considering only the darkest response at each mesoscale area from observations made during intervals 5 days long. Five percent of the signals which gave minimum brightness were selected. This permanent or background brightness is supposed to correspond to the ground, so that the maps show only snow fields which are continuously present for all 5 days. The observed gridpoint may have been bare and dark for the first day of observation and snow-covered afterward, or it may have been bare during the whole week; in both cases the computerized composite product shows bare ground. Generally, the maps tend to show surface patterns from the beginning of the week during fall and winter and from the end of the week in spring and summer.

Our data are plotted at the middle date of the sampled interval. Snow may occur at a given site 3 to 8 days earlier in the fall and 3 to 8 days later in the spring than our plot indicates. No correction was applied to rectify this. Thus, errors of up to 5 days may have resulted from this source on a local scale. Nevertheless, conclusions about the year-to-year changes in character of the same season, on a global scale, could hardly be significantly affected.

There is also a possibility that a sampled set represents clouds rather than snow cover. Visual examinations of daily images are made to detect such

Table 1. Starting dates and durations of snow cover seasons. The seasons are defined in terms of snow and ice cover as follows: SC-spring, (55 to 15) $\times 10^6$ km^2; SC-summer, less than 15×10^6 km^2; SC-fall, (15 to 55) $\times 10^6$ km^2; and SC-winter, more than 55×10^6 km^2.

Year	SC-spring		SC-summer		SC-fall		SC-winter	
	Starting date	Duration (days)	Starting date	Duration (days)	Starting date	Duration (days)	Starting date	Duration (days)
1967			30 July	66	5 October	72	16 December	84
1968	9 March	118	5 July	97	10 October	65	14 December	86
1969	10 March	124	12 July	90	10 October	77	26 December	35
1970	30 January	159	8 July	89	5 October	76	20 December	91
1971	21 March	111	10 July	67	15 September	87	11 December	95
1972	15 March	109	2 July	77	17 September	73	29 November	106
1973	15 March	116	9 July	73	20 September			

errors, but some may have passed unrecognized. In such a case the minimum brightness would also refer to clouds instead of ground. The possibility of error from this source increases in mountains of lower latitudes, where the data density is low and clouds are frequent. Although no quantitative analysis of this source of error is available to us now, we do not expect the hemispheric totals to be significantly affected.

2) The NOAA snow and ice boundary maps were based until 1973 on visible light imagery. Experimental infrared scanning by Nimbus and NOAA-2 satellites was not used in the evaluation of data from the northern hemisphere. The pack-ice boundaries within the Arctic Circle, poorly illuminated from October to March, were reconstructed according to satellite data for the winter of 1967–1968 (*10*) and according to earlier naval observations (*11*). From November through February the arctic pack ice increases gradually by about 5×10^6 km^2. Even with a 20 percent error in our interpolation, which is highly unlikely, we would expect an error of only 2.5 percent in the hemispheric totals for November and less than 2 percent for January. Errors of this order of magnitude could not affect the validity of our conclusions.

3) The area covered by snow and ice was measured by polar planimeter separately in 10° latitudinal belts (except for the zone from 60° to 90°) which are 21 to 25 millimeters wide in the original charts. The results were corrected for area. Errors due to inaccurate drafting of the original charts, planimetry, and the use of parameterized factors for areal corrections are estimated to be less than 2 percent and randomly distributed.

4) Some weekly charts were not available. An especially long gap exists in the winter of 1967–1968, where the curve in Fig. 2 was reconstructed by analogy with the 1968–1969 section. For the springs and summers of 1967, 1968, 1970, and 1971 only every second weekly chart was measured and data in between were visually interpolated. The calculation of monthly means was time-weighted by using only actually measured charts, although the values for Fig. 5 were obtained graphically from Fig. 2. Thus, there is minor disagreement between the two sets.

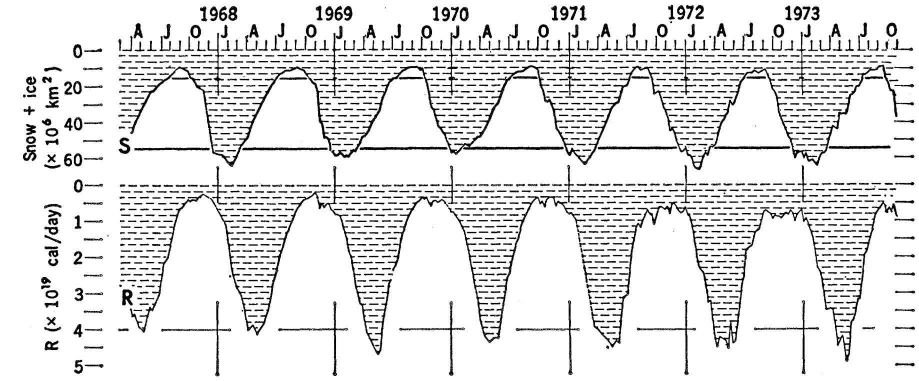


Fig. 2. Variation of the snow and pack-ice cover (*S*) and the reflection index (*R*) in the northern hemisphere from April 1967 to 15 September 1973. The values of 15×10^6 and 55×10^6 km^2 are arbitrarily chosen to subdivide the year into four snow cover seasons (see Table 1). The data are based on NOAA maps showing the average snow and ice boundaries (*1*). Late November and December of 1967 have been reconstructed by analogy with 1968 conditions. The time scale shows the first day of each month; abbreviations are the same as in Fig. 1. Only such cover as stays for at least 5 days was detected.

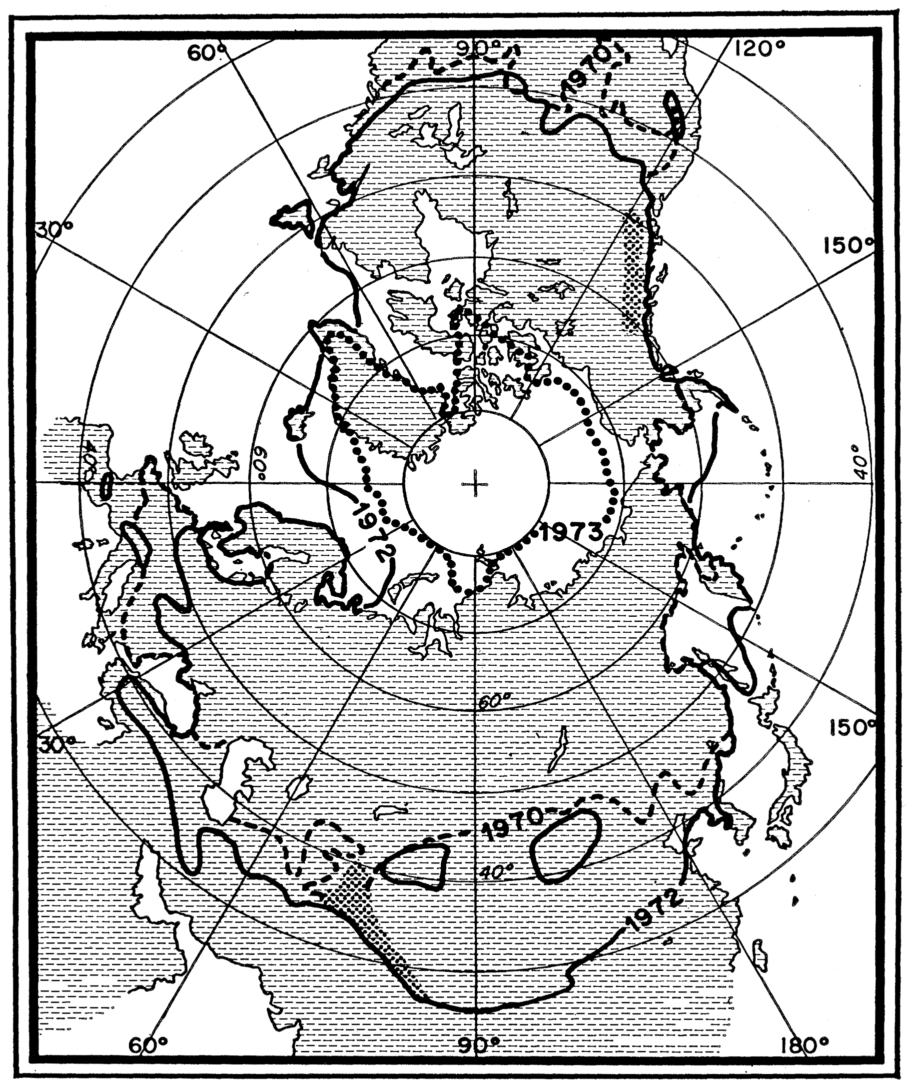


Fig. 3. The snow and ice boundary on 10 February 1972 when the record area of 66.7×10^6 km^2 was covered (solid line) and during the winter maximum of 1 January 1970 (dashed line). Mountain areas where the snow failed to melt in the summers of 1971, 1972, and 1973 are stippled. The pack-ice boundaries of 13 September 1973 (dotted line) show exceptionally large areas of open water. The data are based on NOAA charts (*1*), which show only the cover remaining for at least 5 days.

Reflection Loss

A variation in the size of the snow and ice fields affects the earth's heat balance. Especially large is the impact on the amount of energy reflected from the earth's surface. This quantity varies with the changing reflective properties of a snow field and with the changing amount of radiation reaching the ground. Thus, the mean winter albedo of snow-covered coniferous forests is only about 35 percent, whereas that of the fresh snow in Antarctica may reach 98 percent (*3*). There are no reflection losses on the circumpolar ice fields during the dark polar winters. On the other hand, a relatively large loss occurs early in spring from the patches of snow in the Rockies and the Himalayas, where the insolation is high.

In order to estimate the order of magnitude of the energy diverted from the lower troposphere because of the presence of snow and ice, the reflection loss index R has been introduced (*9*). It is measured in calories per day and is given by

$$R = f \times m \times Q \times S$$

where the parameterized mean annual difference between the albedo of the bare ground or ocean and that of the snow and ice cover is f; it is estimated to be 0.30 (*9*). The parameterized mean extinction of radiation passing through the atmosphere, due to the presence of clouds, is m; it is estimated to be 0.67 (*12*). The global radiation reaching the ground on cloudless days is Q (*12*). Effects of turbidity are zonally averaged. Values for latitudes 35°, 45°, 55°, and 70°N were used to represent corresponding latitudinal belts. The units are calories per square centimeter per day. The area covered by snow and pack ice is S. It is separately measured in four latitudinal belts 90° to 60°N, 60° to 50°N, 50° to 40°N, and below 40°N; the units are square centimeters.

The index R does not refer to the real earth but to the highly simplified model where only two variables, the area covered by snow and ice and the insolation, are allowed to change with time. All other factors are parameterized and fixed. Because of the large approximations made, R must differ considerably from the real amount of reflected radiation. The index is more likely underestimated than overestimated because cloudiness over snow, under normal circumstances, is generally lower than the mean. Also, the southern hemisphere may reflect proportionally more radiation than the R index in Fig. 1 indicates, because the mean albedo in Antarctica is higher than in the snow-covered surfaces of the northern hemisphere. Plots of R are shown in the lower parts of Figs. 1, 2, and 5.

On a global scale (Fig. 1) the reflection loss in 1968 was lowest at the beginning of September and highest in May. The difference represents about 1.9 percent of the mean daily value of the effective incoming radiation reaching the surface of the globe. In the southern hemisphere the maximum loss occurred in November and the minimum in June, while in the north the maximum was reached in May and the minimum in November.

In the northern hemisphere (Fig. 2) data exist for a 7-year-long interval. Repeatedly, the reflection loss was highest in spring and lowest in fall. Maximum R was reached in the springs of 1969 and 1973.

The running annual means (Fig. 5) show the same fast increase during 1971 as the snow cover curve. Even though the R index cannot be directly equated with a loss in the earth's heat balance because of the varying cloudiness, there is no doubt that the surface heat exchange in 1971 must have dropped markedly.

Slight recovery in the annual average values occurred in spring 1973, but the R index still remains high. It was 2.039×10^{19} cal/day as of 1 November 1973.

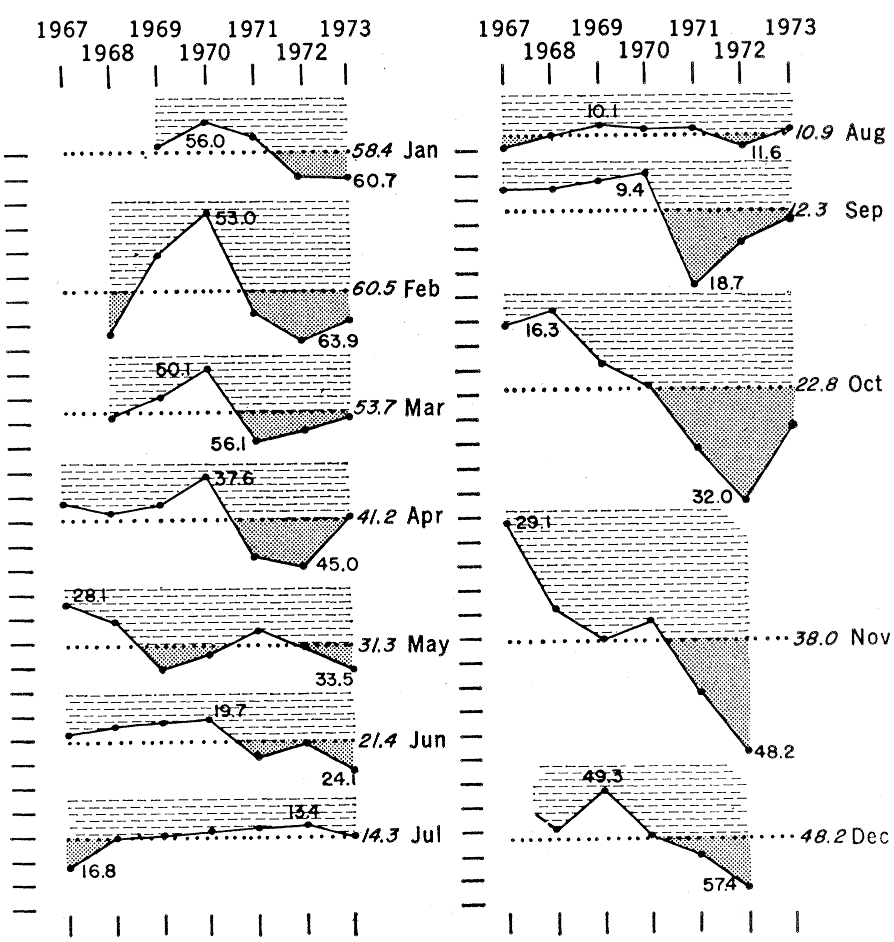


Fig. 4. Time-weighted monthly mean extents of snow and ice cover in the northern hemisphere from 1967 to August 1973. The vertical scale is marked in units of 2×10^{6} km². The numbers are the minimum, maximum, and average values (dotted line) for the month. Note the sharp increase of snow cover from 1970 to 1971 and the continuous increase during October and November until 1972.

Relation to Weather

We were unable to obtain synoptic temperature and precipitation records for the period discussed here. It is nevertheless well known that the principal circulation patterns during 1968 to 1971 were normal or close to normal, whereas the weather of 1972 and the winter and spring of 1973 was in many respects anomalous. Practical consequences of the last two severe winters in Central Asia and in parts of North America are felt today in every American household.

The *Bulletin of the World Meteorological Organization* (*13*) lists scores of record-breaking weather extremes observed during 1972 in both hemispheres and gives the following characteristics of the general circulation patterns during 1972:

The general circulation of the atmosphere in 1972, over both the northern and southern hemisphere, differed considerably from the fairly consistent pattern that had prevailed each year from 1968 to 1971. In the northern hemisphere, the cyclonic activity over the North Atlantic and western Europe was much greater than previously owing to the fact that, after being quite weak for several years, the Icelandic semi-permanent low-pressure system intensified at about the end of 1971. In fact, the zonal circulation index over the North Atlantic area was above normal during the whole of 1972.

In contrast to this situation, the zonal index was lower than normal in the North Pacific area, over eastern and northeastern Europe, and over large parts of western Asia. Over these latter areas there were abnormally strong and lengthy blocking situations, both in winter and summer, with the mean pressure well above normal.

In the tropics and the subtropics, pressure was generally below normal and the tropical activity was in many areas very intense.

In the southern hemisphere, the middle-latitude westerly flow changed into above average in the Pacific area while it remained below normal in the Atlantic. Over other longitudes, long-wave circulation patterns dominated throughout the year without showing any clear persistence.

The general circulation pattern caused the mean temperature distribution, particularly during the winter, to be considerably below normal all over the North American continent and large parts of the mid-Atlantic, as well as over the Mediterranean. Over the Baffin Island area the annual mean temperature was 4°C below normal. On the other hand, a large area of annual mean temperatures above normal, connected with the above-mentioned blocking situations, was found over the European part of the Arctic Ocean, over most of eastern and northern Europe and over western and central Asia. Large parts of these areas were also characterized by long periods of below normal precipitation or droughts having detrimental effects on agricultural production. Dry weather also persisted for most of the year in western and central Europe. Above normal amounts of precipitation were, however, found in East Asia and along the Pacific coast of North America. The Mediterranean countries and the Near East also received precipitation amounts much above normal.

In the southern hemisphere, Australia in particular experienced serious rainfall deficiences for the year.

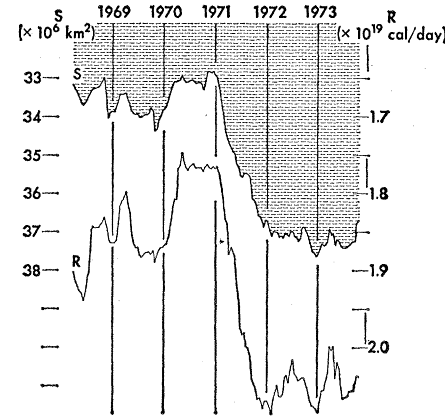


Fig. 5. Running annual means of snow and ice cover (*S*) and of the reflection loss (*R*) plotted on the last day of the period represented. For each year 1 January is marked. The data are graphically sampled from Fig. 2. Both parameters increased drastically during 1971.

Mitchell (*14*) showed that the global surface air temperatures have been dropping for the past 30 years. Dronia (*15*) reported gradual shrinking of the atmospheric column between the 500- and 1000-millibar levels during the last 20 years over much of the northern hemisphere. He also calculated the corresponding decrease of the mean air temperatures. His results for 1968 through 1972 are shown in Fig. 6 and compared with the observed change in the extent of snow cover. The increase in snow cover was accompanied by a decrease in air temperature between 500 and 1000 mbar, especially in the low latitudes. At the same time the temperature increased over the pole.

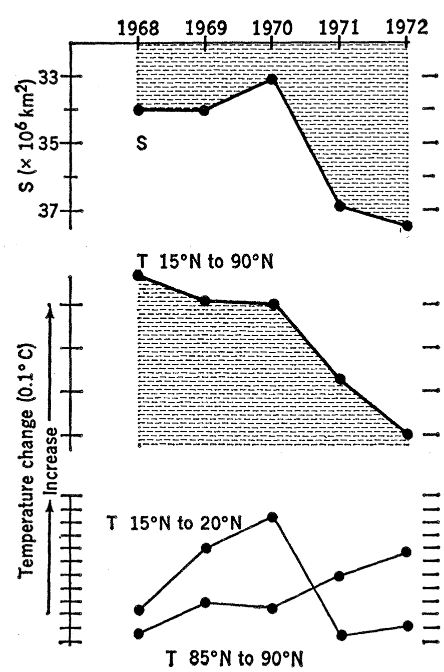


Fig. 6. Annual mean snow and ice cover (*S*) compared with the relative mean temperature of the atmosphere (*T*) between 500 and 1000 mbar (*15*). From 1970 to 1971 the temperature dropped by 0.2°C north of 15°N and by 0.9°C between 15° and 20°N. It increased over the pole.

Thus, the anomalous weather of 1972 was accompanied by exceptionally large snow fields and by a record low in the air temperatures north of 15° latitude. Longer observations and careful meteorological analysis are needed to determine whether this relation was causative or coincidental (*16*).

The shift in snow cover pattern had already developed in 1971, a year before the subsequent weather anomalies (Figs. 4 and 5). The increase in the mean monthly snow cover values for February, March, April, and September 1971 was indeed spectacular, and SC-fall started 3 weeks sooner in 1971 than in any of the four preceding years.

It is still premature to say that the global weather pattern of 1972 was a response to the anomalous snow cover of 1971 and therefore could have been expected. But, in view of the close links connecting the distribution of snow and ice with heat reserves in the oceans and with atmospheric circulation, such a relation is probable. In any case, this is a highly attractive field for research and promises to become increasingly helpful in long-range forecasting (*17*).

Snow and the Climate Change

The mean annual snow and ice cover of the northern hemisphere during the last full glacial is estimated as 60×10^6 to 70×10^6 km², about 30×10^6 more than today. In 1971 the mean annual coverage increased by 4×10^6 km². Only seven similar occasions would be needed to establish the pleniglacial surface albedo. In view of this, the observed short term variation in surface albedo is surprisingly large. Naturally, anomalies of this magnitude do not occur often, and in the intervening periods normal circulation patterns tend to return. But the potential for fast changes of climate evidently does exist on the earth and should be kept in mind (*18*).

The short-term changes in the distribution of heat due to the variation of snow and pack-ice fields are considerably larger than those directly produced by fluctuations in incoming extraterrestrial energy. Could snow magnify the effect of these minute fluctuations (*19*)? We might also investigate in detail the circulation regimes during the snow accumulation season; the interiors of the Asian and American continents, where the largest variation was observed (*9*); and the secular variations in the Antarctic pack ice, whose mean area in July and August increased by about 10 percent from 1966 to 1970 (*8*).

In any case, the role of snow and ice in year-to-year weather variation seems to be substantial and calls for the close attention of meteorologists and climate modelers.

Conclusions

Routine mapping of snow and ice fields in the northern hemisphere was started by NOAA in 1967. Large year-to-year variations of the snow and pack-ice covers were observed. The annual mean coverage increased by 12 percent during 1971 and has remained high. The index *R*, which shows the approximate amount of energy reflected from the surface by snow and ice under the mean cloudiness, increased correspondingly. Thus, if the cloud cover over the snow fields did not increase substantially, the anomalous weather patterns of 1972 and 1973 could have been connected with the deficit in surface heat exchange which originated in the northern hemisphere the year before. During the past 7 years the largest changes occurred in the fall and in the continental interiors of Asia and America (*8*).

Two synoptic parameters which could readily provide information on the development of snow and ice cover in the northern hemisphere are (i) the total area momentarily covered and (ii) the running annual mean of snow and ice coverage for the preceding 1-year period. By 20 September 1973 the annual mean coverage was 37.3×10^6 km^2, 11 to 12 percent higher than at the same time during 1968 through 1970. Snow cover–fall, the season when 15×10^6 to 55×10^6 km^2 of the northern hemisphere is covered with snow and ice, started on 20 September 1973, compared to 17 September 1972 and 5 or 10 October during 1967 through 1970.

The links between the atmosphere, the oceans, and the land surfaces must be better understood before the role of snow and ice can be thoroughly explained and exploited for long-range weather forecasting. But it is clear that snow, hitherto almost overlooked in synoptic meteorological reports, must be important in the mechanism of weather changes.

References and Notes

1. *Northern Hemisphere: Average Snow and Ice Boundaries.* These are maps in polar stereographic projection edited once a week by NOAA's National Environmental Satellite Service, Suitland, Maryland. The original photographic signals received from Advanced Vidicon Camera Systems (ARVS) on board satellites of the ESSA, ITOS, and NOAA series refer to a nominal grid of 40 by 40 km. For more information see text and A. H. Booth and V. R. Taylor, *Am. Meteorol. Bull.* **50**, 431 (1969); E. P. McClain and D. R. Baker, *NESC Technical Memorandum 12* (National Environmental Satellite Center, Suitland, Md., 1969).
2. M. I. Budyko, *Tellus* **21**, 612 (1969); W. D. Sellers, *J. Appl. Meteorol.* **8**, 392 (1969).
3. K. Ya. Kondratyev, *Radiation in the Atmosphere* (Academic Press, New York, 1969); V. V. Mukhenberg, *Trans. Main Geophys. Obs. Leningr.* **139**, 43 (1963); E. C. Kung, R. A. Bryson, D. H. Lenschow, *Mon. Weather Rev.* **92**, 543 (1964).
4. J. O. Fletcher, in *Beneficial Modifications of the Marine Environment*, S. F. Singer, Ed. (National Academy of Sciences, Washington, D.C., 1972); M. S. Marshunova, *Tr. Arkt. Antarkt. Nauch. Issled. Inst.* **229**, 5 (1961); M. P. Langleben, *J. Glaciol.* **11**, 337 (1972).
5. T. W. Schlatter, *J. Appl. Meteorol.* **11**, 1048 (1972).
6. P. A. Shumskiy, A. N. Krenke, and I. A. Zotikov [in *Research in Geophysics*, vol. 2, *Solid Earth and Interface Phenomena*, H. Odishaw, Ed. (MIT Press, Cambridge, Mass., 1964), p. 425] give the maximum extent of snow in the northern hemisphere as 85×10^6 km^2 and in the southern hemisphere as 41×10^6 km^2. The maximum extent of the earth's surface bearing snow cover at least briefly is given as 126×10^6 km^2. Their figures are considerably higher than ours, but maps derived from satellite data show only snow fields that remain for at least 5 days. Even so, their figure of 72.5×10^6 km^2 as the annual mean extent of ice and snow is unbelievably high.
7. N. A. Streten, in preparation.
8. J. E. Sissala, R. R. Sabatini, H. J. Ackermann, *Polar Rec.* **16**, 367 (1972).
9. G. J. Kukla and H. J. Kukla, *Quat. Res. (N.Y.)* **2**, 412 (1972). Because several weekly NOAA charts were not available to us in 1972, the dating of some winter maxima differs from our recent figures.
10. The maps for these two winters were produced by visual interpretation of basic data. Areas poorly illuminated for computer analysis may be successfully studied by an experienced observer.
11. L. Koch, *Medd. Gronland* **130** (No. 3), 1 (1945).
12. T. G. Berland, *Trans. Main Geophys. Obs. Leningr.* **18**, 80 (1949).
13. J. M., *Bull. World Meteorol. Organ.* **22**, 99 (1973).
14. J. M. Mitchell, Jr., *Ann. N.Y. Acad. Sci.* **95**, 235 (1961); updated in *Quat. Res. (N.Y.)* **2**, 436 (1972).
15. H. Dronia, *Beil. Berlin. Wetterkarte* **90/73**, 1 (1973).
16. P. F. Clapp [*J. Appl. Meteorol.* **6**, 1018 (1967)] finds close relations between snow frequency and temperature; H. H. Lamb [*Q. J. R. Meteorol. Soc.* **81**, 172 (1955)] finds the same with pressure.
17. J. Namias, *J. Geophys. Res.* **75**, 565 (1970).
18. V. P. Starr and A. H. Oort [*Nature (Lond.)* **242**, 310 (1973)] come to a similar conclusion. Evidence for exceptionally fast changes of climate in the past exists in the geological record; see G. J. Kukla, R. K. Matthews, M. J. Mitchell, *Quat. Res. (N.Y.)* **2**, 261 (1972); J. P. Kennett and P. Huddlestun, *ibid.*, p. 384; W. Dansgaard, S. J. Johnsen, H. B. Clausen, C. C. Langway, *ibid.*, p. 396.
19. The existence of such a feedback mechanism was first proposed by J. Croll [*Climate and Time in Their Geological Relations* (Stanford, London, ed. 4, 1890), p. 75] in a remarkably clear formulation of the concept of the earth's heat budget. J. Kukla [*Geol. Mijnbouw* **48**, 307 (1969)] referred to this feedback as the "snow cover heat reaction."

20. We thank J. D. Hays, N. D. Opdyke, J. Imbrie, A. McIntyre, A. H. Oort, R. K. Matthews, and J. M. Mitchell for reading the manuscript, and J. Winston and T. Gray from the National Oceanic and Atmospheric Administration and J. O. Fletcher from the National Science Foundation for valuable advice. Supported by NSF grant GX 28671-K. This article is contribution No. 2053 from Lamont-Doherty Geological Observatory of Columbia University.