30 October 1981, Volume 214, Number 4520 SCIENCE

Summer Ice and Carbon Dioxide

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Summary. The extent of Antarctic pack ice in the summer, as charted from satellite imagery, decreased by 2.5 million square kilometers between 1973 and 1980. The U.S. Navy and Russian atlases and whaling and research ship reports from the 1930's indicate that summer ice conditions earlier in this century were heavier than the current average. Surface air temperatures along the seasonally shifting belt of melting snow between 55° and 80°N during spring and summer were higher in 1974 to 1978 than in 1934 to 1938. The observed departures in the two hemispheres qualitatively agree with the predicted impact of an increase in atmospheric carbon dioxide. However, since it is not known to what extent the changes in snow and ice cover and in temperature can be explained by the natural variability of the climate system or by other processes unrelated to carbon dioxide, a cause-and-effect relation cannot yet be established.

Annually averaged surface air temperatures in the Northern Hemisphere generally decreased from the early 1940's through at least the middle 1960's (*1*, *2*). In contrast, numerical climate models have predicted continuous global warming due to increasing atmospheric carbon dioxide (*3*–*5*). Several reasons have been offered to explain this apparent discrepancy. The warming may have been delayed by the thermal inertia of the oceans (*6*, *7*), or the CO_2 concentrations may still be too low to overcome the cooling caused by volcanic dust (*8*), man-made aerosols (*9*), or a possible decrease of solar luminosity (*10*).

Carbon dioxide warms the troposphere largely by absorption of longwave radiation escaping the earth's surface. The process is amplified by two positive feedbacks: (i) snow/albedo feedback, in which the ground along the snow margin heats the air, accelerating further melt, and (ii) water vapor feedback, in which the relatively moist and warm air accelerates surface evaporation.

Because of the snow/albedo feedback, most climate models show the largest warming in the high or middle latitudes, although they differ about which season is most sensitive. Some predict that the largest temperature change will occur in winter and others that it will occur in summer (*4*–*6*, *11*, *12*). In agreement with modeling results of Ramanathan *et al.* (*4*), we expect the effect of CO_2 to be greatest along the marginal belt of snow and ice fields during late spring and summer, when the surface net radiation balance is positive and the evaporation from unfrozen water bodies is relatively high. Since atmospheric CO_2 has gradually risen since the second half of the last century (*13*), the surface air temperatures and snow and ice fields during late spring and summer should indicate gradual warming. The effect should be strong over the pack ice in the Southern Hemisphere, where the concentration of high-altitude aerosol, a presumed cooling agent, is relatively low (*14*).

In this article we examine the changes in the surface air temperature and in the areas of snow and sea ice. Since these have a high year-to-year variability (*12*, *15*) and are affected by many processes unrelated to CO_2, it is not possible within the scope of the present study to establish a cause-and-effect relation between the observed variations and carbon dioxide.

Southern Hemisphere Sea Ice

Observations of surface air temperature in the high southern latitudes are few and the records comparatively short. Better data exist on the extent of the seasonal sea ice field, which has been relatively accurately depicted by satellites since 1973 and has been reconstructed from ship reports for earlier years.

Satellite monitoring. Data for the period 1973 to 1980 were obtained by analyzing weekly sea ice charts produced by the Navy-NOAA (National Oceanic and Atmospheric Administration) Joint Ice Center. Visible, infrared, and microwave satellite images as well as conventional observations are used in the confection of these charts (*16*). The original Navy information was recorded by means of a grid overlay in 2° latitudinal belts within several longitudinal segments. Five categories of ice concentration were differentiated. Details of this procedure and boundaries of the geographic sections can be found elsewhere (*17*). Time series of indices representing the areal extent (square kilometers) of ice (S), parameterized surface albedo (A_s), percent of open water (together with dark ice) within the pack ice perimeter (w), and an absorption index (q) have been produced (*18*). The data were interpolated in time to represent a standard 52-week set.

Index A_s is based on parameterized values of surface shortwave albedo for various snow and ice concentrations. Values for water and bare ground, averaged from published data (*19*), are kept constant.

The q index for a specified latitude (ϕ) and time interval (t) is related to the amount of shortwave radiation absorbed

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 0036-8075/81/1030-0497$01.00/0

at the surface under fixed atmospheric conditions. It is a function of surface albedo and insolation measured in calories per week:

$$q(\phi, t) = I_0(\phi, t)\,[1 - A_s\,(\phi, t)]\,7ka$$

where I_0 is the mean midweek daily insolation received by a horizontal surface at the top of the atmosphere (*20*); A_s is the surface albedo index; k is the atmospheric attenuation factor, taken as 0.4 (*21*); and a is the area.

Figure 1A shows the seasonal variation in the area of the Antarctic sea ice, including areas of open water in the ice (polynyas), averaged for the interval 1974 to 1978. The weekly range for 1973 to 1980 is also shown. The maximum extent is attained between late August and early October, and the minimum in early February. Ice dissipation in late spring and summer takes an average of 16 weeks and is fastest in November and December. The ice buildup in fall and winter takes approximately 22 weeks. Our observations compare favorably with those reported by Rayner and Howarth (*22*) and by Fletcher (*23*). Figure 1B shows the average (1974 to 1978) seasonal cycle and range of the open water index w. The average value of the index ranges from less than 1 percent in winter to as much as 34 percent in February (*24*).

The absorption index q quantifies the potential effect of the observed ice variations on the surface heat budget in the high latitudes. The average seasonal cycle of q between 1974 and 1978 in the belt 50° to 90°S is shown in Fig. 1C, with weekly maxima and minima. As might be expected, the variance is largest from November through January, when the insolation is high. The difference between 1973 and 1980 illustrates how large the potential effect on the heat budget could be. Surface radiation measurements or detailed information on cloud distribution will be needed to determine how closely the q index parallels the actual heat balance.

The mean weekly rate of change of q (Fig. 1C) peaks in mid-November and at the beginning of March. Assuming that there were no systematic large-scale changes in zonal cloudiness during the interval analyzed, the surface south of

Table 1. Monthly Antarctic sea ice extents derived from Russian (*29*) and U.S. (*33*) atlases published in 1966 and 1957, respectively, compared with average, maximum, and minimum sea ice extents observed in 1973 to 1980.

Source	Sea ice extent ($\times 10^6$ km^2)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
U.S. atlas	8.4	6.4	4.5	7.7	11.1	15.3	16.5		20.1	20.2	17.8	13.3
Russian atlas	8.7	6.1	4.2	8.9	11.1	13.7	16.7	18.5	20.8	20.7	17.8	13.8
Observations in 1973 to 1980												
Mean	6.2	4.0	4.7	7.0	10.0	13.3	16.1	17.8	18.5	18.1	16.3	11.2
Maximum	9.1	5.6	6.8	8.7	11.5	14.7	17.6	19.2	20.5	20.1	18.8	13.7
Minimum	4.4	2.8	3.3	5.1	7.7	11.7	14.3	16.5	16.7	17.0	15.1	9.9

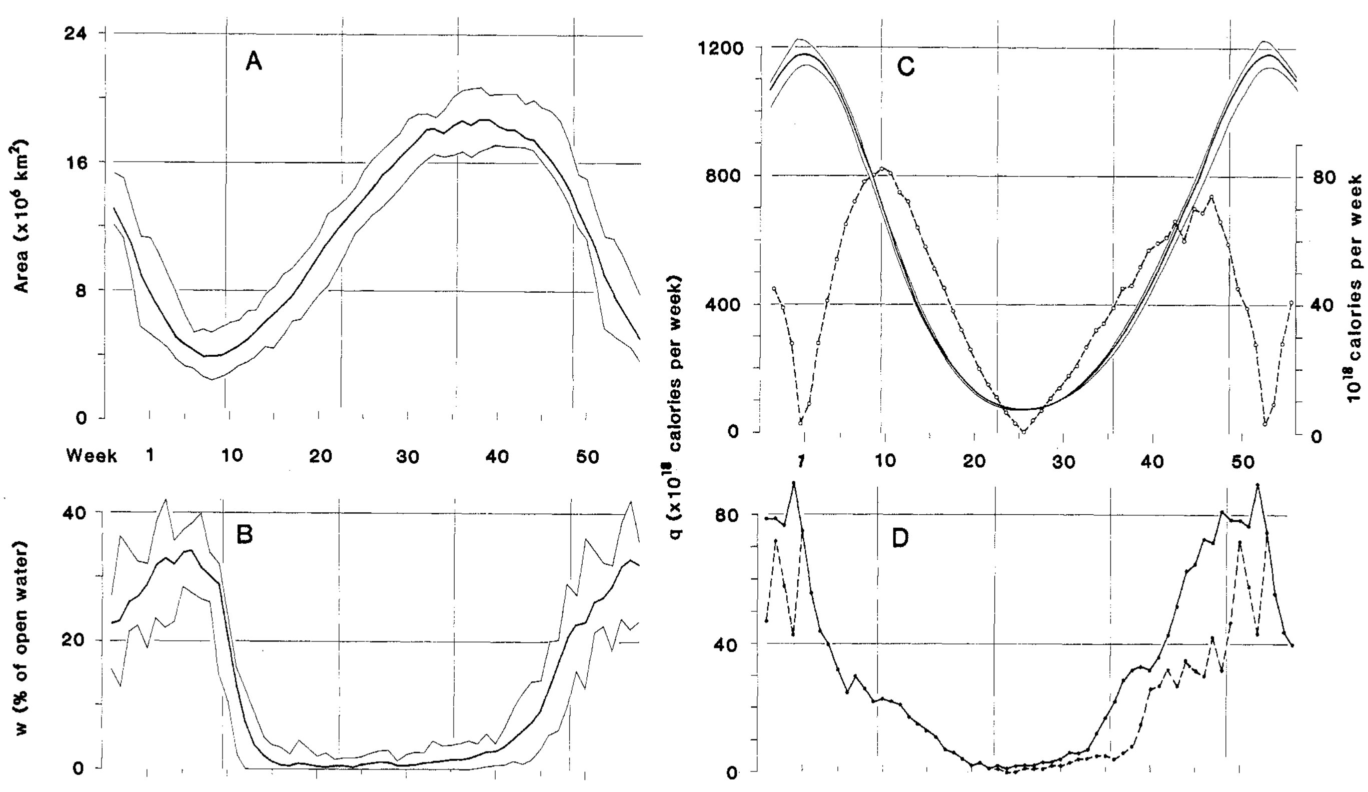

Fig. 1. (A) Seasonal cycle of total sea ice area around Antarctica in concentrations greater than 1 tenth or 1 octa. Polynyas are included. The heavy line shows the 1974–1978 average; lighter lines show the weekly maximum and minimum from the 1973–1980 interval. (B) As in (A) for the percentage of open water (w), including polynyas within the pack ice boundary. (C) As above for q index, which is related to the energy absorbed at the surface between 50° and 90°S. The dashed line shows the 1974–1978 mean weekly rate of change in q (scale at right), irrespective of sign. (D) Weekly range of q in the 1973–1980 interval (heavy line) and difference between 1973 and 1980 (dashed line).

50°S absorbed 1060×10^{18} calories more in 1980 than in 1973, which is about 4 percent of the 1974–1978 average annual total (2.73×10^{22} calories).

The mean ice extent decreased markedly from 1973 through December 1980, as shown by the 12-month running means in Fig. 2. The reduction occurred in all seasons (*25*). The average extent in summer (December to February) decreased from 8.2 million to 5.7 million square kilometers.

A projection of long-term trends is not possible from the 8-year-long data set. Periodic variations on the time scale of a few years to decades are known in oceanic circulation (*26*) and are likely to affect the sea ice distribution as well. Heap (*27*) reported variations in sea ice extent on the order of 2 to 4 years and 10 years in the vicinity of the Antarctic peninsula and the Weddell Sea. The observed change between 1973 and 1980 is thus likely to be associated with a short-term oscillation (*28*).

Ship reports. To find out how the average and extreme ice extents recently observed compare with those of the presatellite era, we examined the mean monthly ice boundaries depicted in two atlases.

The Russian *Atlas Antarktiki* (*29*) was based on information obtained from various Russian, U.S., and Japanese expeditions between 1947 and 1962 and on data gathered in the 1930's. Observations made in more recent years were given preference in the analysis. Geographically, coverage was poorest for the northeast sector of the Ross Sea, the Bellingshausen Sea, and the central Weddell Sea (*30*). We derived the monthly mean areas by the same procedure used with the current charts. The results are shown in Table 1 (*31, 32*).

A maximum extent of 20.6×10^6 km^2 is found in September and a minimum of 4.2×10^6 km^2 in March. The Russian atlas shows a greater ice extent than the 1973–1980 average in all months except March. The current maximum is exceeded in February, April, September, October, and December.

The *Oceanographic Atlas of the Polar Seas* (*33*) was published by the U.S. Navy in 1957, 9 years before the Russian atlas. All available past observations were used in the analysis, including data collected on expeditions between 1939 and 1957 in which the Navy participated. The seasonal maximum is shown in September and October and the minimum in March. For all months except March, the atlas shows more ice than the 1973–1980 average, and the recent maximum is exceeded in February, June, and October (Table 1).

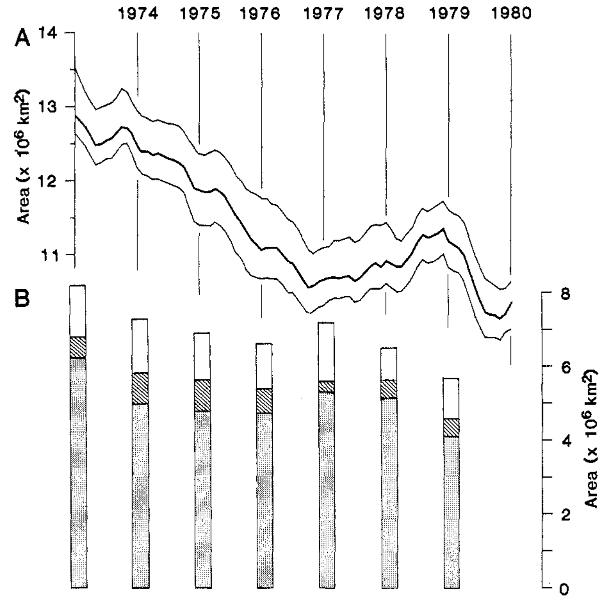

Fig. 2. (A) The 12-month running mean of Antarctic sea ice area. The upper curve shows concentrations > 1 octa, the middle curve concentrations > 4 octas, and the lower curve the net area of ice, excluding water and thin dark ice. Curves are plotted at the terminal date for the interval January 1973 through December 1980. (B) Average summer (December to February) ice extent through February 1980 in the three concentrations in (A) is shown by vertical columns. Net ice area is stippled.

Several other charts showing monthly mean ice extent have been produced, including the British Admiralty's *Ice Chart of the Southern Hemisphere*, published in 1943 (*34*). As reported by Pease (*32*), the British chart shows more ice in summer than both the U.S. and Russian atlases.

Charts showing the approximate mean positions of the ice (*35*) and the ice limits in individual years (*36*) were produced by Hansen. The latter were reconstructed from ship reports during four whaling seasons between 1929 and 1934 and cover the area between 40°W and 110°E. The ice limits are shown for the beginning and middle of the month from October through March. Subsequently, Mackintosh and Herdman (*37*) published charts for each month of the year, based on reports of the Discovery Committee's ships (*38*), factory ship logs, and other miscellaneous sources. Each observation that gave evidence of being at or near the ice edge is separately plotted and dated. Their report includes data from the middle of the 19th century through 1938. Information for April through September is too scarce to allow any meaningful comparison with the present regime.

Reports for the longitude sector 35°W to 115°E from 1929 through 1938 are compared with present summer ice positions in Fig. 3 (*39*). The average, minimum, and maximum latitudes of ice in concentrations greater than 1 octa for 1973 to 1980 were taken from the Navy charts. Data for the 1930's were taken from the charts of Hansen (*36*) and Mackintosh and Herdman (*37*).

Figure 3 shows that most of the reported ice positions from November through February lie north of the 1973–1980 average. Many appear close to or north of the current maximum, particularly in November and December. Table 2 includes data from areas outside the sector 35°W to 115°E and shows that 82 percent of all available observations around Antarctica for November to February are north of the current average latitude. This is in agreement with observations for early summer between 1923 and 1932, when the ice edge appears to have been well north of the South Orkney Islands and near South Georgia Island in 1926, 1928, and 1930 (*27*). Thus, in general, late spring and summer pack ice during the 1930's between 60°W and 100°E appears to have been heavier than the recent average.

The first known ice observations made by Captain James Cook during his circumnavigation of Antarctica between 1772 and 1775 were compiled by Herdman (*40*). These observations and the data of Mackintosh and Herdman (*37*) for the 19th century are summarized in Table 3. With so few records, it is not possible to reach any firm conclusion about the ice conditions during this period. However, it is interesting to note that exceptionally high numbers of iceberg sightings were reported in the South Atlantic in the 1850's and 1890's (*41*) and again in the 1920's and 1930's (*42*).

Data limitations. A comparison of satellite-derived charts and ship reports on ice edge positions is not without problems. An observer aboard ship viewing a distant ice field can overestimate the ice concentration. Narrow sea ice plumes can extend far into the open ocean and can be mistaken for the ice edge. In the Weddell Sea, a large ice tongue frequently develops in late summer. Different ice edge positions could then be reported for the same longitude, depending on the direction of the ship's approach.

Records from the 1930's are not equally distributed in time and space. Observations are scarce between 100°W and 120°E and their number varies from year to year, with about three-fourths of the summer data coming from the 1930–1934 pentad. Reports of the absence of ice were scarce, which could bias the results toward heavier coverage (*37*). The U.S. and Russian charts are composites that do not represent a homogeneous average either geographically or in time. It is possible that the ice edges in the atlases are biased toward heavier ice conditions in order to secure an extra margin of safety for shipping. It should also be borne in mind that the sector between 60°W and 100°E includes a zone of the highest seasonal and year-to-year variability in the ice extent (*43*).

We assume, nevertheless, that given the consensus of relatively large numbers of independent reports, our basic interpretation is correct. Several observations lend support to such a conclusion. Budd (*44*) has shown that larger sea ice areas and longer sea ice seasons are inversely correlated with surface air temperatures at coastal stations. An increase in mean annual surface air temperatures at higher latitudes between 1955 and 1974 was reported by Damon and Kunen (*45*), although the warming was not uniform in space and time (*46*). Summer sea surface temperatures around most of Antarctica south of 60°S were lower in 1920 to 1934 than in 1945 to 1955, with the exception of the northern Ross Sea and the northern tip of the Antarctic peninsula (*47*).

Northern Hemisphere

Variation of surface air temperatures in the Northern Hemisphere has been described by many researchers (*1, 2, 48, 49*). Gruza and Ran'kova (*50*) report mean zonal monthly temperatures along selected latitudes for the interval 1891 to 1978. A comparison of the 1934–1938 and 1974–1978 pentads, based on their data, shows the 1970's to be cooler during most of the year, particularly in autumn (*51*). However, recent temperatures have been higher during January, April, and June at 55°N, during May at 65°N, and from June through August at 80°N. With the exception of January and June at 55°N, these positive anomalies appear to be associated with the seasonally shifting belt of melting snow.

In order to define the latitudinal progression of the snow belt, we derived zonal surface albedo estimates for land from the NOAA Snow and Ice Boundary Charts (*52, 53*). The range was determined from weekly data for 1974–1979 separately for each 2° belt. Figure 4 shows the zone in which the 1974–1978 mean weekly albedo falls between 33 and 66 percent of this range. In our analysis, the changes of surface albedo are solely a function of varying snow extent. Therefore the zone plotted in the figure is closely related to the margin of seasonally shifting snow cover.

The results of the energy balance model of Ramanathan *et al.* (*4*) indicate that this is also the zone where a CO_2 increase is expected to have the largest local impact. Figure 4 shows where the temperature is predicted to rise more than 4°C as a result of the CO_2 doubling. The sensitivity is highest in spring and summer and increases with latitude. Thus, the positive temperature departures in 1974 to 1978 appear to be associated with the seasonally shifting belt of melting snow and, at the same time, with the zone of highest predicted sensitivity of surface air temperatures to increased CO_2.

At this stage, the observed relation should be viewed with caution. The zonal mean temperature for 80°N is determined from a limited number of observations. In addition, station density was considerably lower in the 1930's than in the 1970's (*54*).

Observations on secular changes in Arctic sea ice extent do not indicate that there is less ice now than there was in the

Table 2. Antarctic ice edge positions between 1928 and 1938 compared to those at present. Each entry shows the number of observations north of the 1973–1980 mean in the numerator and the total number of observations in the same period and longitudinal sector in the denominator. Values are also summarized for all longitudes. Also shown are the number of observations north of the recent maximum position, south of the recent minimum position, and within the current range.

Longitude sectors	Jan.	Feb.	Mar.	Apr.–Sept.	Oct.	Nov.	Dec.	Nov.–Feb.	Whole year
1° to 20°W	7/7	3/3		1/1	3/3	9/9	7/7	26/26	30/30
21° to 40°W	2/2		5/5	1/1	5/5	8/8	3/4	13/14	24/25
41° to 60°W	4/4	6/6	1/2	6/10	1/1	0/1	6/6	16/17	24/30
61° to 80°W	3/5	2/2	1/1	0/3	0/1	3/5	3/8	11/20	12/25
81° to 100°W	5/7	1/4	3/3		0/1	1/1		7/12	10/16
101° to 120°W	0/1		0/1			1/1		1/2	1/3
121° to 140°W	0/1	0/1	0/1					0/2	0/3
141° to 160°W	0/1	2/2		1/1				2/3	3/4
161° to 180°W	1/2			1/1				1/2	2/3
179° to 160°E	2/3					2/2		4/5	4/5
159° to 140°E	0/1		1/1	1/1				0/1	2/3
139° to 120°E	0/1		0/2	1/1	0/1			0/1	1/5
119° to 100°E	4/6	0/1	2/4		1/1	1/3	1/4	6/14	9/19
99° to 80°E	13/13	6/7	5/8		5/5	5/6	4/4	28/30	38/43
79° to 60°E	4/4	4/5	3/3		1/1	4/4	9/9	21/22	25/26
59° to 40°E	3/8	8/12	2/3	2/2		8/8	11/12	30/40	34/45
39° to 20°E	6/6	8/11	8/15	4/4	4/5	9/11	17/17	40/45	56/69
19°E to 0°	5/5	3/4	3/4	7/8	2/9	10/10	14/14	32/33	44/54
				All sectors combined					
North of mean	59/77	43/58	34/53	25/33	22/33	61/69	75/85	238/289	319/408
Percent	77	74	64	76	67	88	88	82	78
North of maximum	12/77	17/58	13/53	12/33	8/33	32/69	36/85	97/289	130/408
Percent	16	29	25	36	24	46	42	34	32
South of minimum	4/77	1/58	0/53	1/33	1/33	0/69	1/85	6/289	8/408
Percent	5	2	0	3	3	0	1	2	2
In range	61/77	40/58	40/53	20/33	24/33	37/69	48/85	184/289	268/408
Percent	79	69	75	61	73	54	57	64	66

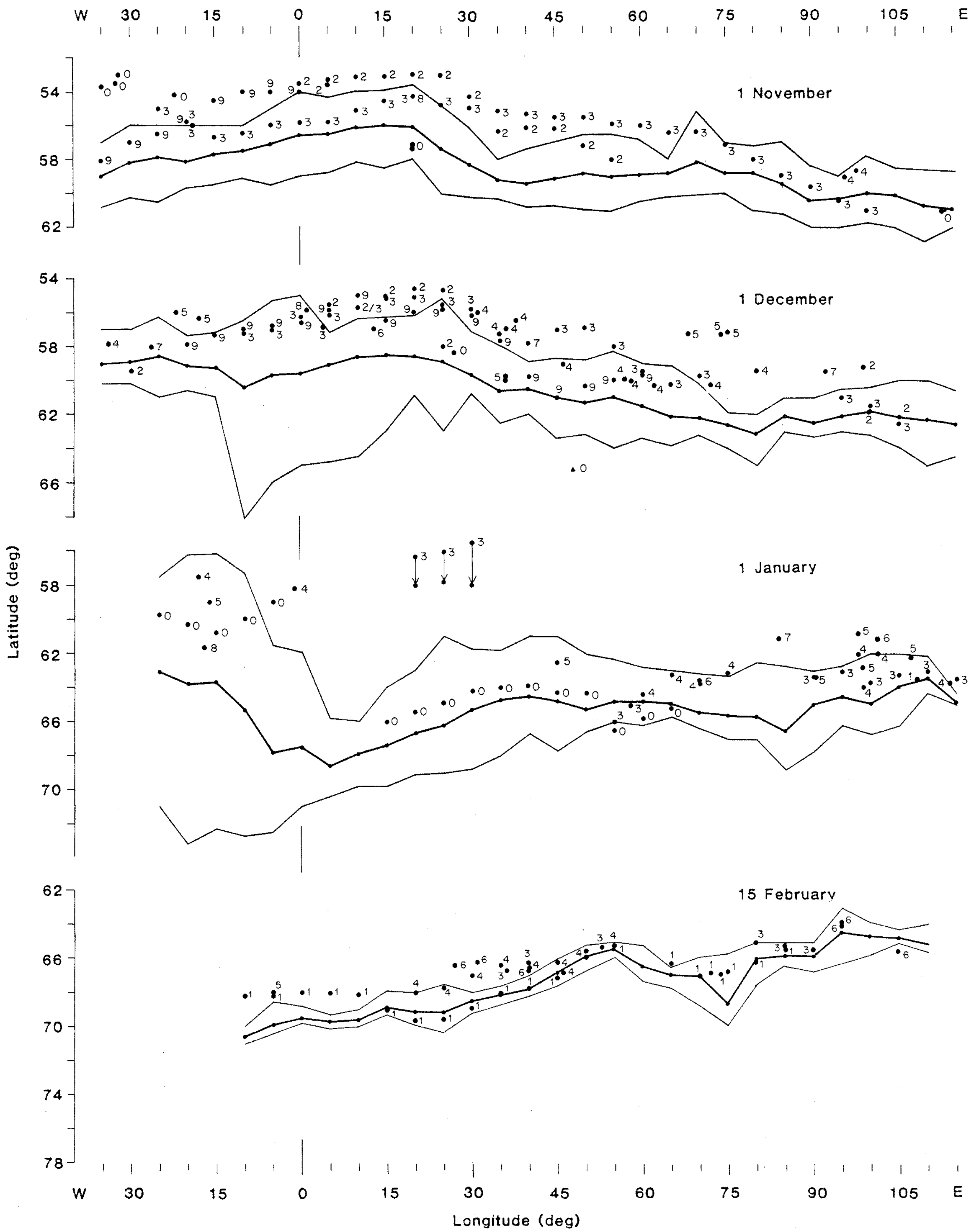

Fig. 3. Latitudinal ice positions for 1929 to 1938 as charted by Hansen (*36*) and Mackintosh and Herdman (*37*) between 35°W and 115°E compared with the 1973–1980 averages (heavy line) and maximum and minimum extents (lighter lines). The last digit of the year is shown. Data plotted for the first of the month are in the range −3 to +5 days; those plotted for the middle of the month are in the range ±3 days. The ordinate scale shows latitudes from north (top) to south (bottom).

1930's; however, the information is restricted to peripheral Arctic seas (*55*). Large regional out-of-phase fluctuations are known to exist between the North Atlantic and the Bering, Chukchi, and Beaufort seas (*25, 56*). It is not yet known what part of the Arctic is indicative of hemispheric climatic trends. More complete coverage of Arctic ice is available from 1953. Walsh and Johnson's analysis (*56*) shows lighter conditions between 1953 and 1964 than between 1965 and 1977.

Recent spring and summer snow extent as derived from satellite imagery has not shown a decrease either (*25, 53*). Probability charts of snow cover for the presatellite era were constructed from ground station reports by Dickson and Posey (*57*). A comparison of their charts with the 1974–1980 average snow lines shows the recent boundary from November through April to be farther south in North America but little changed in Eurasia (*58*). Several problems make a comparison on a hemispheric scale unreliable, particularly in late spring (*59*).

Changes in the extent of melting snow cover in the central Arctic during the summer are not known. By the end of June or early July, snow on top of the ice melts throughout the Arctic Basin. The meltwater released from dissipating snow gathers in puddles and eventually siphons through the underlying ice into the ocean below. As a result, the regional albedo in the central Arctic drops sharply from about 0.8 to 0.6 or 0.5 and the water vapor content in the troposphere rises from negligible amounts to about 2 grams per square centimeter (*60*). The timing of the melt and the area affected vary considerably from year to year, as does the surface heat exchange and the evaporation rates. If Gruza and Ran'kova's (*50*) conclusion about recent warming in the high Arctic from June through August is correct, then the area affected should be more extensive in recent years. Since the energy balance model of Ramanathan *et al.* (*4*) shows exceptionally high sensitivity to CO_2 in this area, a program of detailed monitoring of the Arctic summer snow melt is highly desirable.

However, it is equally important to determine the cause of the recent cooling during other seasons, particularly autumn. Zonal mean surface air temperatures in autumn were found to be substantially lower during the 1974–1978 pentad than during 1934 to 1938 (*51*). The difference for October is 4.8°C at 80°N, 1.5°C at 65° and 55°N, and 1.3°C at 40°N. It would be of interest to examine the possible effects of increases in man-made aerosols on the regional climate as a function of season (*61*).

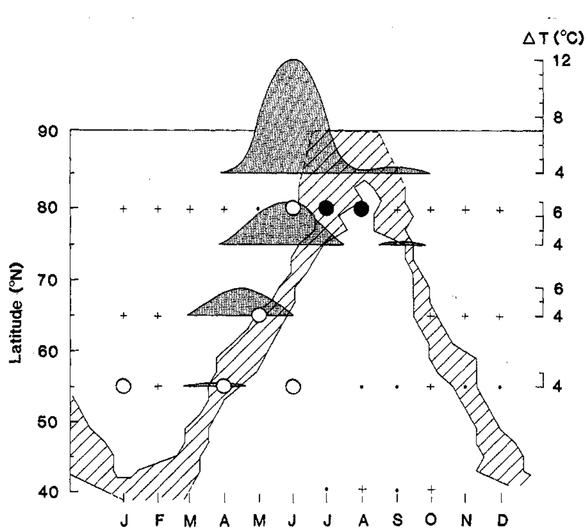

Fig. 4. Association of recent positive temperature anomalies (circles) with the belt of melting snow (hatching) and the CO_2 sensitive zone of Ramanathan *et al.* (*4*) (stippling). (●) Difference between 1974–1978 and 1934–1938 zonal mean monthly surface air temperatures (*51*) greater than 0.5°C; (○) differences between 0.1° and 0.5°C; (dot) negative departures larger than −0.5°C; (+) negative departures equal to or larger than −1.0°C. The snow margin is defined as the zone where the 1974–1978 mean weekly surface albedo was between 33 and 66 percent of the multiyear range. Intervals along 55°, 65°, 75°, and 85°N, where Ramanathan *et al.* (*4*) predict an increase of zonal mean temperatures > 4°C due to CO_2 doubling, are stippled. The scale of the predicted temperature increase is shown on the right.

Table 3. Ice edge positions in the 18th and 19th centuries compared to those at present. Of a total of 11 observations (December to February), 5 were north of the present average, 4 were north of the present maximum, 1 was south of the present minimum, and 6 were within the range of present positions.

18th and 19th centuries		Present (1973 to 1980)		
Date	Approximate ice position	Average ice position	Maximum ice position	Minimum ice position
14 to 17 December 1772	22°E, 54.9°S	60.9°S	57.3°S	65.0°S
24 December 1773	138°W, 67.3°S	66.0°S	62.2°S	70.0°S
10 December 1820	165°E, 62.2°S	64.6°S	62.7°S	66.5°S
18 December 1841	148°W, 62.3°S	66.1°S	61.9°S	70.5°S
8 December 1894	171°E, 66.0°S	65.1°S	62.0°S	67.2°S
30 December 1898	154°E, 62.0°S	65.3°S	64.1°S	65.9°S
18 January 1773	40°E, 67.3°S	66.3°S	62.0°S	68.0°S
30 January 1774	107°W, 71.2°S	69.5°S	67.5°S	70.5°S
1 January 1841	170°E, 66.8°S	66.0°S	65.0°S	68.5°S
9 January 1841	175°E, 69.8°S	69.0°S	64.7°S	77.5°S
3 February 1895	172°E, 66.8°S	75.6°S	67.0°S	77.8°S

Conclusions

The information for the two hemispheres and our conclusions may be summarized as follows:

1) The multiyear variability in the extent of Antarctic sea ice is considerable and has a large potential impact on the energy budget of the middle and high southern latitudes.

2) Late spring and summer ice around Antarctica during the last few years has been less extensive than that reported in several atlases published before 1970. Pack ice between 60°W and 100°E appears to have been more extensive from November through February in the 1930's than at present.

3) The observations outlined above agree qualitatively with the expected effect of a CO_2 increase.

4) The mean surface air temperatures along selected northern latitudes between 55° and 80°N during spring and summer were higher in 1974 to 1978 than in 1934 to 1938. The positive anomalies appear to be associated with the seasonally shifting belt of melting snow.

5) The observation above is consistent with the temporal and spatial impact of increasing CO_2 predicted by the energy balance model of Ramanthan *et al.* (*4*).

6) Our results suggest that studies of highly variable components of the climate system such as snow and pack ice fields and the associated surface air temperatures should be given priority in the search for early signs of a CO_2 effect.

7) Since it is not known to what extent the observed changes in snow and sea ice areas and in surface air temperature can be explained by natural fluctuations or by processes unrelated to CO_2, any conclusions about a relation between the observed departures and a CO_2 increase are, at present, highly tentative.

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52. See M. Matson and D. R. Wiesnet (*53*) for a description of the charts and G. Kukla and J. Gavin (*17*) and G. Kukla and D. Robinson (*19*) for the procedure used.
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61. The possible impact of man-made aerosols on climate has been discussed by many authors, including R. A. McCormick and J. H. Ludwig [*Science* **156**, 1358 (1967)] and P. V. Hobbs, H. Harrison, and E. Robinson [*ibid.* **183**, 909 (1974)]. J. Hansen, D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell [*ibid.* **213**, 957 (1981)] in their prediction of potential effects of CO_2 on climate do not take the possible increase of man-made high-altitude aerosols into account. A realistic prediction of future climate will have to consider the combined impact of all variables capable of altering regional climate particularly in the key industrial and agricultural areas.

62. This subject was originally discussed on 24 March 1981 at a Richard Foster Flint Lecture at Yale University. Suggestions of H. van Loon, G. Weller, T. Barnett, N. Untersteiner, S. Ackley, W. S. Broecker, K. Hunkins, and two anonymous reviewers helped to improve the manuscript. The work has been supported by grant ATM 80-01470 from the Climate Dynamics Program of the National Science Foundation. This is Lamont-Doherty Geological Observatory Contribution 3228.