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An Analysis of the Recent Extreme Winters in the Contiguous United States

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ABSTRACT

Analysis of monthly-mean temperature and precipitation data for each of the 48 contiguous United States for the 1976–77 through 1978–79 winter seasons shows that the temperature and precipitation departures from the long-term means were extreme. The consecutive occurrence of such severely cold winters is unprecedented in the available 85-year record.

Variability of temperature and precipitation has increased in the past 5-year period, compared to previous pentads, mainly as a result of much greater frequency of extreme anomalies. An "extreme anomaly" is defined as a mean monthly or seasonal value exceeding two standard deviations from the long-term mean.

Statistical estimates of average return periods of winter mean temperatures equal to or lower than the actual values recorded for the past three seasons are close to the empirical values. However, the implausibly low probabilities for the occurrence of consecutive severe winters suggest that the development of large-scale anomalies in atmospheric circulation, which these low temperatures represent, may have a common dynamical forcing and that these forcing mechanisms possess time scales on the order of several years.

1. Introduction

The recent large deviations from the long-term mean climate have given rise to speculation that the climate may be entering a new, more variable phase (Lansford, 1975). The worldwide occurrence in this decade of unusually severe winters, widespread droughts with crop failures on the one hand and major floods on the other, have spurred public concern about the possibility of major climatic swings and attendant disruptions (Hare, 1977; Odingo, 1977).

This paper compares the three consecutive winter seasons from 1976–77 through 1978–79 relative to an 85-year record of temperature and precipitation for each of the 48 contiguous United States. Winter mean temperature is the average of December, January and February; monthly-mean temperatures are based on means of daily averages for each reporting station, for each month, which are combined to form first, divisional averages and then areally weighted to determine state values. Precipitation values are seasonal totals. Schaal and Dale (1977) and Nelson *et al.* (1979) showed that changes in the configuration, location and observing practices of the states' observation network are likely to introduce nonclimatic biases in the state temperature series. However, these corrections are, at most, on the order of 0.6°C (1°F) and thus are not likely to appreciably change the results of this study. The effect of location and configuration changes on state precipitation is not known, but is likely to be within the natural error variance or uncertainty of the estimated area-mean due to sampling variability within the state network.

The winters, which will be called 1977, 1978 and 1979, respectively, were truly extraordinary in terms of the extreme temperature and precipitation anomalies that were recorded in the United States (Figs. 1 and 2). The fact that they occurred consecutively adds further significance to the anomalies. The 1977 winter was notable for its extreme January cold, attendant fuel shortages and transportation disruptions, and extreme drought in the West. We described this winter in great detail in an earlier paper (Diaz and Quayle, 1978), noting that January 1977 was, up to that time, probably the coldest month during the period of instrumentally measured data in the United states. This was based both on an areally weighted average for the contiguous 48 states and individual long-term station records. It is remarkable that January 1979 has since broken that record.

Namias (1978a) analyzed some of the factors that contributed to the extreme departures in the atmospheric circulation that occurred over North America during the 1976–77 season. He concluded that a series of complex atmospheric, oceanic and cryospheric factors operated in a synergistic man-

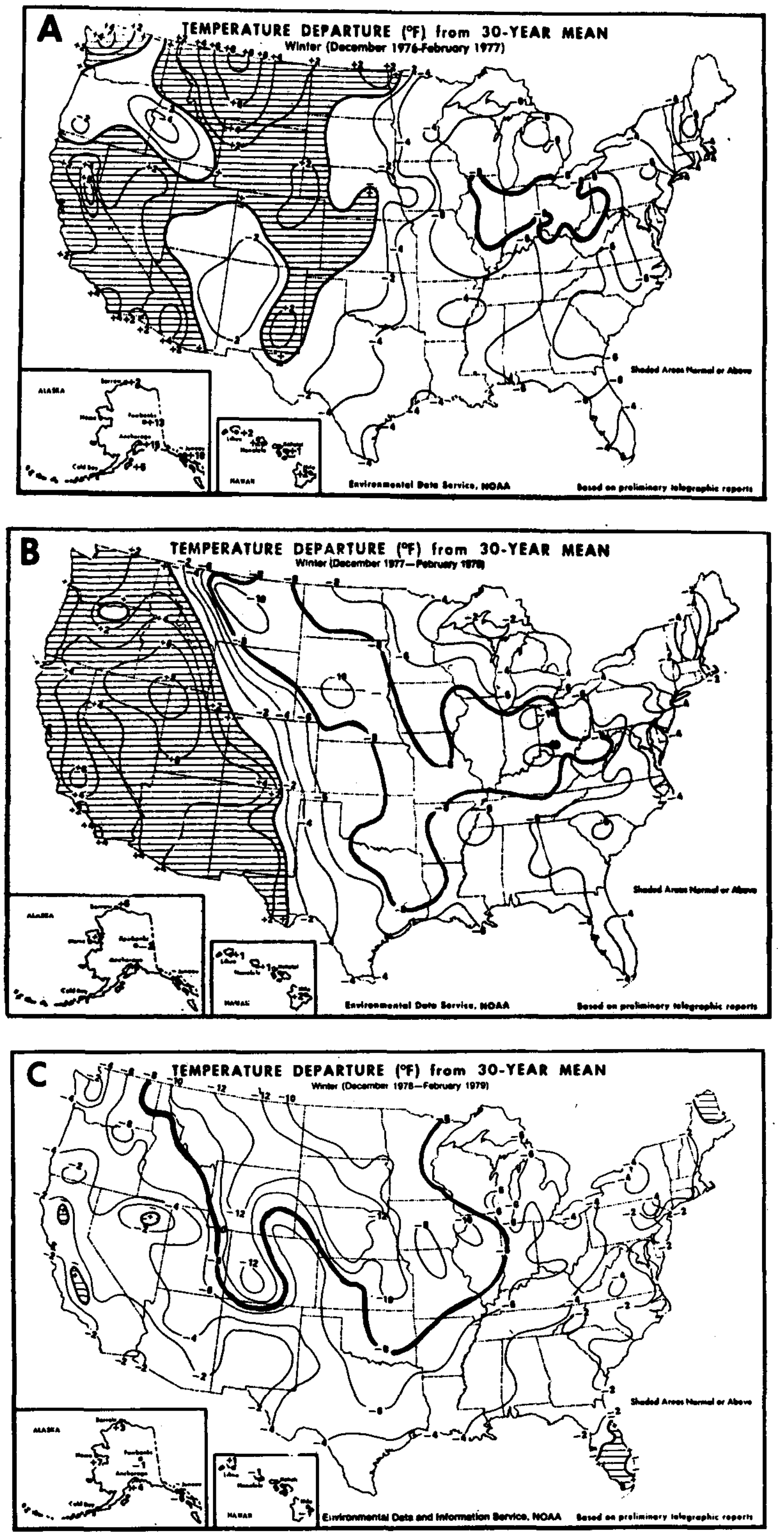


FIG. 1. Winter temperature departure (°F) from 1941–70 normal in (a) 1976–77 season, (b) 1977–78 season and (c) 1978–79 season. Taken from *Weekly Weather and Crop Bulletin*, Environmental Data and Information Service, National Oceanic and Atmospheric Administration.

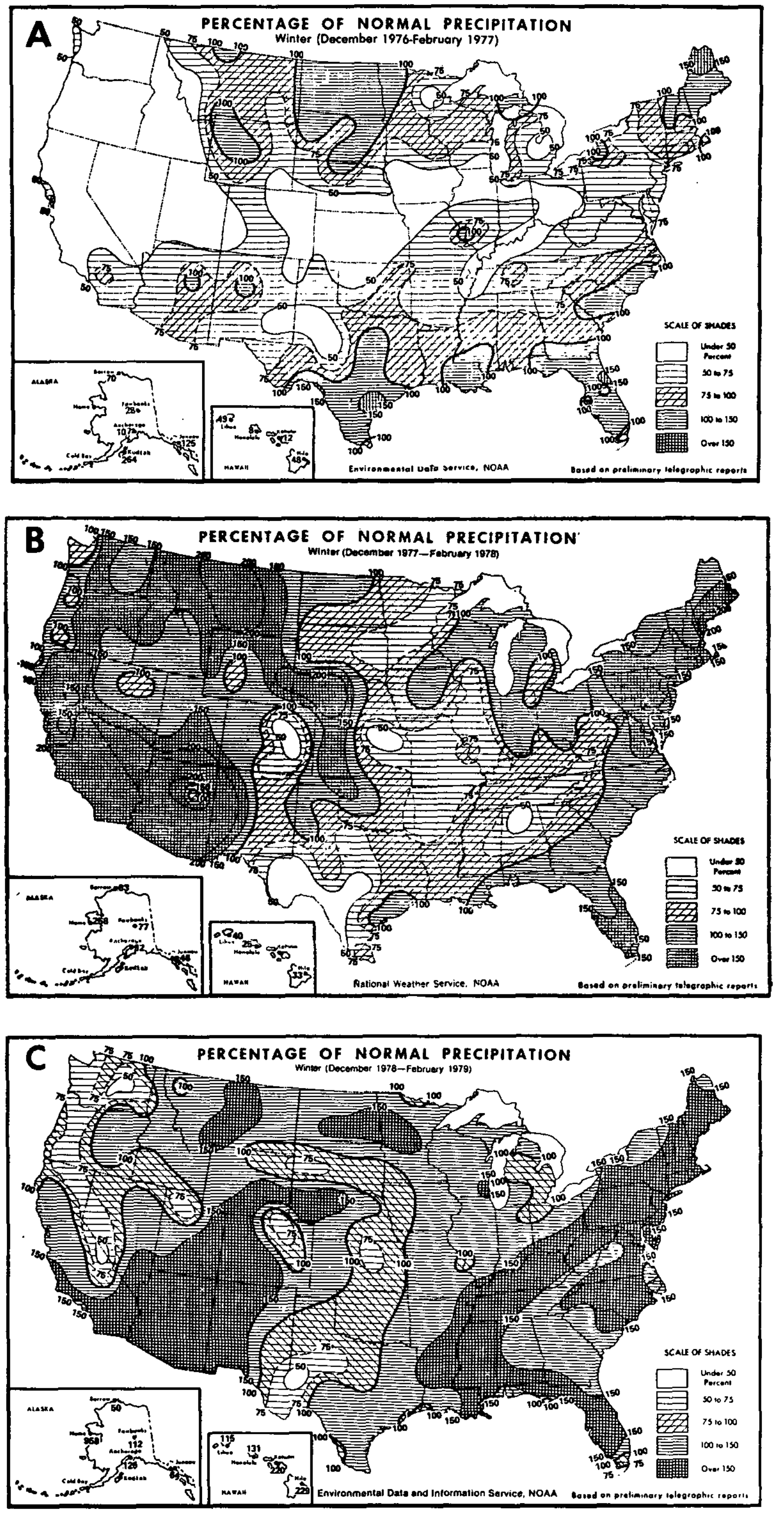


FIG. 2. Percentage of 1941–70 normal winter precipitation for (a) 1976–77 season, (b) 1977–78 season and (c) 1978–79 season. Taken from *Weekly Weather and Crop Bulletin*, EDIS, NOAA.

ner, developing positive feedback loops which resulted in the occurrence of persistent, widespread abnormalities that lasted from early fall through most of the winter season.

The 1978 winter was memorable for a number of reasons. Severe cold was accompanied by several intense low-pressure systems which brought very heavy snows to the Midwest, Middle Atlantic and New England regions. The extreme 2-year drought in the West was decisively broken by a series of storms that brought heavy precipitation, with serious flooding, to California and the southwestern states and a heavy snowpack to the Sierras and the Colorado Rockies (Shelton, 1978; Doesken *et al.*, 1978). The 1978 winter temperature anomalies exceeded 5.6°C (10°F) below normal in a few areas. Compared to the severe winter of 1977, the area of greatest negative departures was displaced further to the west; the area enclosed by the $-4.4°\mathrm{C}$ ($-8°\mathrm{F}$) anomaly isopleth was considerably larger and extended into central Montana, where a year earlier, temperatures had been considerably above normal. It was warmer than normal throughout most of the Mountain region west of the Continental Divide with positive temperature departures extending westward to the Pacific Coast.

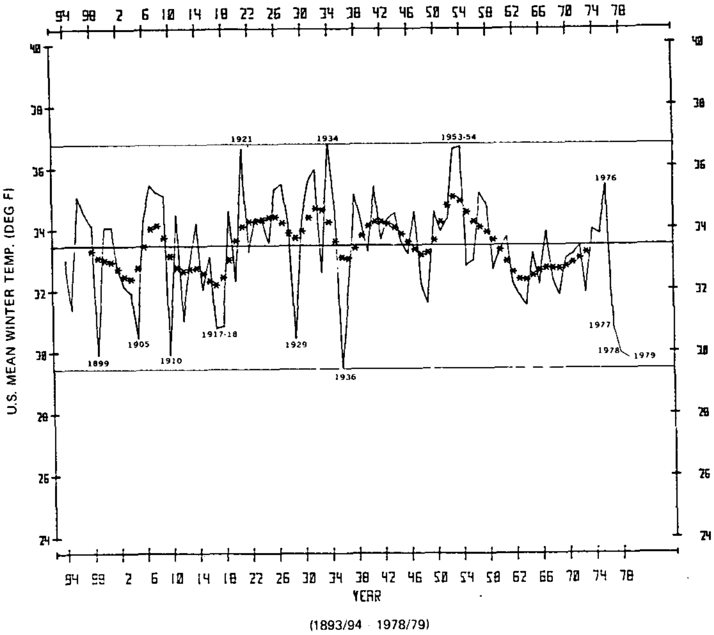
The 1979 season established an unprecedented (in the modern record) string of three consecutive severe winters with colder-than-normal average temperatures over nearly all of the contiguous United States. January 1979 had the coldest monthly average temperature on record. The extent of the negative departures (~98% of the nation) appears to be unprecedented in the available historical record. The $-4.4°\mathrm{C}$ ($-8°\mathrm{F}$) anomaly isopleth covered an area equivalent to that in 1978, but shifted farther west.

2. Seasonal comparisons

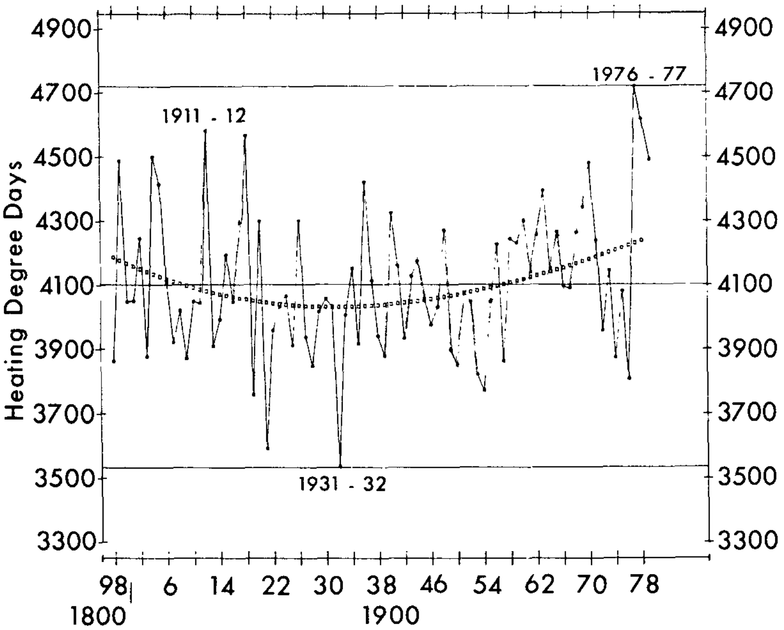
Because of the duration and location of the cold temperatures over the populous eastern half of the nation in the 1977 season, population-weighted heating-degree-day totals for the contiguous United States, which provide an index by which heating energy demand can be assessed, registered an all-time high. A plot of winter mean temperature (starting with the 1893–94 season) and total October–March population-weighted heating degree days [base 65°F (18.3°C)] for the contiguous United States for the period 1897–98 through 1978–79 is shown in Fig. 3. A 9-point Gaussian low-pass filter is used to smooth out high-frequency fluctuations in the winter temperature series (starred curve). A third-order least-square polynomial is shown for the heating-degree-day curve (squared curve). Census figures from 1970 are used for population weights so that correlations with fuel consumption will be representative of contemporary demographic patterns. It should be noted that unlike the year 1977, cool temperatures continued to prevail during most of 1978, which caused the annual mean temperature to rank third coldest for the period since 1893.

A comparison of mean 700 mb heights for the three months December, January and February for the winters of 1977, 1978 and 1979 (see *Monthly Weather Review* for March, April and May of these years) suggests some similarities in the mean circulation over the North American continent during the first two seasons; however, a substantial westward shift of the long-wave ridge-trough system occurred in 1979. During all three seasons, a long-wave ridge was positioned over the western part of the continent (offshore in 1979) with an associated deep low downstream in eastern Canada. During 1977 and 1978, the locations of the lows (at their deepest during January) varied from each other mainly in terms of latitude. The mean trough axes in 1977 and 1978 were located roughly between 70 W and 80°W, with minimum 700 mb heights somewhat north of 50°N in 1977 but close to 70°N in 1978. The trough center was close to 60°N, 90°W in 1979. The combination of western ridge and eastern trough promoted the funneling of cold arctic air to the United States in persistent outbreaks throughout these winter seasons.

The airflow over the western United States was significantly different in all three winters. The ridge, which in 1977 had deflected most cyclonic systems northeastward to the Gulf of Alaska was, in 1978, positioned further east and was somewhat weaker, with a tendency to split at lower latitudes. Doesken *et al.* (1978) noted that the winter of 1977 was characterized by pronounced dryness throughout the troposphere, a consequence of the large-scale subsidence to the east of the long-wave ridge, and the absence of storms over the Rockies due to the blocking effect of the ridge. West of about 100°W the mid-tropospheric flow in 1977 was predominantly from the northwest. During the 1978 season, however, this area experienced westerly or southwesterly flow which brought about an influx of moist air of Pacific origin. This flow allowed an increased number of storm systems to penetrate the southwestern United States, although it prevented the Pacific northwest from sharing fully in the surfeit of water that followed. Both Washington and Oregon received only slightly more than their normal seasonal precipitation (Table 1 and Fig. 2). It is worth noting that the western drought was most severe in California; furthermore, the extreme dryness that prevailed during the 1976–77 season was preceded (in California, but not in Oregon or Washington) by a dry 1975–76 season,



OCTOBER-MARCH NATIONAL POPULATION-WEIGHTED HEATING DEGREE DAYS (1897-98 — 1978-79)



The smooth line is a 3rd order polynomial least-squares fit.

FIG. 3. Mean winter temperature (°F) for the United States weighted by area (top) and total October–March heating degree days (65°F base) for the United States weighted by population.

when only about half the normal seasonal precipitation from October to March was measured.

Namias (1978b) examined the atmospheric conditions prevailing and preexisting the great western drought of 1976–77. While persistent, large-scale subsidence throughout the West Coast, and California in particular, can be identified as the immediate cause of the drought, Namias showed that air-sea interactions over the North Pacific going back to the fall of 1975 and winter of 1975/76

TABLE 1. Areally weighted total precipitation and percent of normal (based on the 1897–1976 mean) for December–February and October–March.

State	December–February total precipitation (inches) 1975–76	1976–77	1977–78	Percent of normal precipitation (1897–1976) 1975–76	1976–77	1977–78	October–March total precipitation (inches) 1975–76	1976–77	1977–78	Percent of normal precipitation (1897–1976) 1975–76	1976–77	1977–78
California	4.74	3.68	18.75	39.6	30.7	156.6	9.78	6.50	26.87	51.4	34.2	141.3
Oregon	11.40	3.37	12.67	102.5	30.3	113.8	21.00	7.70	20.73	106.1	38.9	104.7
Washington	19.71	7.02	16.04	131.7	46.9	107.1	36.12	14.50	27.79	134.1	53.8	103.2

could have instigated and maintained the drought through mutual dynamic and thermodynamic readjustments.

The changes in the atmospheric circulation and Pacific sea surface temperature patterns during the latter half of 1977 which foreshadowed the end of the western United States drought have also been discussed by Namias (1979). He points out that fall 1977 height anomalies at 700 mb differed strongly from the corresponding pattern in 1976. In particular, the strong region of positive anomaly (exceeding three standard deviations from the mean) in the Pacific Northwest was replaced by a negative anomaly. Sea surface temperature (SST) changes in the eastern and North Pacific Ocean also were consistent with the observed mid-tropospheric circulation changes. North Pacific SST anomalies for September–November 1976 exceeded −2.2°C (−4°F) whereas for the same period in 1977 SST anomalies over these regions had for the most part reversed.

In sharp contrast to the previous two seasons, the pattern of 700 mb heights in winter of 1979 promoted the channeling of very cold arctic air into the western half of the United States. The pattern was most pronounced during December and January when record or near-record cold temperatures were recorded in Wyoming and Colorado. Montana and the Dakotas also experienced severe and prolonged cold weather. In February, the deepening of the trough in the area of the Canadian maritime provinces combined with a vast reservoir of extremely cold air in eastern Canada to give the Northeast one of its coldest Februarys on record (Ludlum, 1979).

TABLE 2. Coldest 12 months in the United States 1895–1979 (weighted average of the 48 contiguous states).

Rank	Year	Month	Temperature (°F)
1	1979	January	22.8
2	1977	January	23.9
3	1930	January	25.1
4	1940	January	25.4
5	1918	January	25.6
6	1963	January	25.7
7	1912 & 1937	January	26.5
8	1978	January	26.7
9	1899 & 1936	February	27.2
10	1978	February	28.0

Among the notable features of the 1979 winter are the following: 1) January 1979 set a new record for the coldest month on record nationally (Table 2), surpassing the previous record set by January 1977; 2) based on a 13-year record, snow and ice cover in North America exceeded the previous maximum values which were set consecutively in each of the preceding two seasons (Wiesnet and Matson, 1979); 3) record ice cover occurred throughout the Great Lakes—during February (except for Lake Erie) coverage was close to 100% (Assel and Quinn, 1979); and 4) extremely low temperatures during February in the Northeast were coupled with record or near-record snowfall amounts in the middle Atlantic States. New York tied its coldest temperature on record when −46.7°C (−52°F) was measured at Old Forge on 18 February.

Tables 3 and 4 summarize the extremes in temperature and precipitation recorded during the 1977 through 1979 winters. The tables list those states where January, February, December–February or January–February periods in the 1977 to 1979 seasons rank among the three coldest, wettest or driest on record. The extent and severity of the cold temperatures during these winter seasons is evident. January 1977 was the coldest on record for 15 of the contiguous 48 states and the second or third coldest on record for an additional 11. Six states recorded their coldest December–February period in the 1976–77 season and for another nine it was their second or third coldest winter. In 11 states the January–February period was the second or third coldest on record. 1977 had the driest January and the driest December–February period on record in Idaho and Oregon. The 1977 season was also the driest winter season

TABLE 3. Ranking of monthly and seasonal mean temperature extremes record since 1895.

	1976–77			1977–78			
STATE	JAN 1977	DEC–FEB 1976–77	JAN–FEB 1977	JAN 1978	FEB 1978	DEC–FEB 1977–78	JAN–FEB 1978
AL	COLDEST	2ND COLDEST	2ND COLDEST	3RD COLDEST	2ND COLDEST	COLDEST	COLDEST
AR					2ND COLDEST	COLDEST	COLDEST
CT	3RD COLDEST						
DE	2ND COLDEST				3RD COLDEST		COLDEST
FL	2ND COLDEST	3RD COLDEST	3RD COLDEST	3RD COLDEST	3RD COLDEST	2ND COLDEST	2ND COLDEST
GA	COLDEST	COLDEST	2ND COLDEST	2ND COLDEST	2ND COLDEST	2ND COLDEST	COLDEST
IL	COLDEST	3RD COLDEST			COLDEST	COLDEST	2ND COLDEST
IN	COLDEST	2ND COLDEST	3RD COLDEST		COLDEST	COLDEST	COLDEST
IA	3RD COLDEST					3RD COLDEST	
KS					3RD COLDEST	3RD COLDEST	2ND COLDEST
KY	COLDEST	2ND COLDEST	2ND COLDEST		COLDEST	COLDEST	COLDEST
LA	2ND COLDEST	3RD COLDEST		3RD COLDEST	2ND COLDEST	COLDEST	COLDEST
MD	2ND COLDEST				2ND COLDEST		2ND COLDEST
MA	COLDEST			2ND COLDEST			
MS	2ND COLDEST	2ND COLDEST		3RD COLDEST	2ND COLDEST	COLDEST	COLDEST
MO	3RD COLDEST				2ND COLDEST	2ND COLDEST	2ND COLDEST
NE					3RD COLDEST	2ND COLDEST	3RD COLDEST
NJ	COLDEST				3RD COLDEST		
NY	2ND COLDEST				2ND COLDEST		
NC	COLDEST	COLDEST	2ND COLDEST		2ND COLDEST	2ND COLDEST	COLDEST
ND	COLDEST						
OH	COLDEST	COLDEST	2ND COLDEST		COLDEST	2ND COLDEST	COLDEST
OK					3RD COLDEST		COLDEST
PA	COLDEST	COLDEST	2ND COLDEST		3RD COLDEST	COLDEST	COLDEST
RI	2ND COLDEST						
SC	COLDEST	COLDEST	2ND COLDEST		2ND COLDEST	2ND COLDEST	COLDEST
SD				3RD COLDEST			
TN	COLDEST	2ND COLDEST	2ND COLDEST	2ND COLDEST	COLDEST	COLDEST	COLDEST
TX						2ND COLDEST	COLDEST
VA	COLDEST	3RD COLDEST				3RD COLDEST	COLDEST
WV	COLDEST	COLDEST	2ND COLDEST		COLDEST	2ND COLDEST	COLDEST
WI	2ND COLDEST						

	1978–79			
STATE	JAN 1979	FEB 1979	DEC–FEB 1978–79	JAN–FEB 1979
AR	3RD COLDEST		2ND COLDEST	2ND COLDEST
CO	2ND COLDEST		COLDEST	COLDEST
CT		3RD COLDEST		
DE		2ND COLDEST		
IL	3RD COLDEST	2ND COLDEST	2ND COLDEST	COLDEST
IN		2ND COLDEST		COLDEST
IA	2ND COLDEST	2ND COLDEST	2ND COLDEST	2ND COLDEST
KS	2ND COLDEST		COLDEST	COLDEST
KY				3RD COLDEST
LA				3RD COLDEST
MD		2ND COLDEST		
MI		3RD COLDEST		
MN	3RD COLDEST		2ND COLDEST	2ND COLDEST
MO			COLDEST	COLDEST
MT			2ND COLDEST	
NE	COLDEST		COLDEST	2ND COLDEST
NH		3RD COLDEST		
NJ		2ND COLDEST		
NY		2ND COLDEST		
ND			2ND COLDEST	2ND COLDEST
OH		2ND COLDEST		3RD COLDEST
OK	2ND COLDEST		COLDEST	3RD COLDEST
PA		COLDEST		3RD COLDEST
RI		2ND COLDEST		
SD	2ND COLDEST		2ND COLDEST	3RD COLDEST
TX	COLDEST		3RD COLDEST	3RD COLDEST
VT		2ND COLDEST		
VA		3RD COLDEST		
WI			2ND COLDEST	
WY	3RD COLDEST		COLDEST	

TABLE 4. Ranking of monthly seasonal total precipitation extremes record since 1895.

	1976-77				1977-78			
STATE	JAN 1977	FEB 1977	DEC-FEB 1976-77	JAN-FEB 1977	JAN 1978	FEB 1978	DEC-FEB 1977-78	JAN-FEB 1978
AZ								2ND WETTEST
CA			DRIEST	3RD DRIEST				
CO			DRIEST					
DE						2ND DRIEST		
ID	DRIEST	3RD DRIEST	DRIEST	DRIEST				
IN		3RD DRIEST	3RD DRIEST			3RD DRIEST		
IA			3RD DRIEST					
KY			DRIEST					
ME							DRIEST	
MD			DRIEST	DRIEST	2ND WETTEST	3RD DRIEST		
MA								3RD WETTEST
MI						3RD DRIEST		
MS						3RD DRIEST		
MT		3RD DRIEST					2ND WETTEST	
NV			DRIEST					
NH						2ND DRIEST		
NJ					WETTEST			
NY					WETTEST	2ND DRIEST	2ND WETTEST	
NC					3RD WETTEST	3RD DRIEST		
OH			DRIEST	3RD DRIEST		DRIEST		
OR	DRIEST		DRIEST	DRIEST	2ND DRIEST			
PA			3RD DRIEST	3RD DRIEST	WETTEST			
TN			3RD DRIEST			3RD DRIEST		
UT			DRIEST					
VT						DRIEST		
VA			3RD DRIEST	DRIEST		2ND DRIEST		
WA	3RD DRIEST		DRIEST	2ND DRIEST				
WV			DRIEST	DRIEST		3RD DRIEST		
WY		3RD DRIEST	2ND DRIEST					

1978-79

STATE	DEC-FEB 1979	JAN-FEB 1979
AZ	2ND WETTEST	
CT	3RD WETTEST	WETTEST
DE	WETTEST	WETTEST
KY	3RD WETTEST	
LA		2ND WETTEST
MD	WETTEST	WETTEST
MA		WETTEST
MS	2ND WETTEST	WETTEST
NH		3RD WETTEST
NJ	WETTEST	WETTEST
NY	WETTEST	2ND WETTEST
PA	WETTEST	WETTEST
RI	2ND WETTEST	WETTEST
SC		WETTEST
VA	2ND WETTEST	2ND WETTEST
WV	WETTEST	2ND WETTEST

on record in California, Colorado, Nevada and Washington. Interestingly, it was also the driest winter in Ohio and Pennsylvania.

The winter of 1978 followed with another avalanche of records. It was the second or third coldest January in eight states, the coldest February in six states and the second or third coldest in an additional 17. It was the coldest December–February period in nine states and the second or third coldest winter in another 12. The mean for January–February was the lowest in 17 states and second or third lowest in six more states. A very wet January in the eastern United States was followed by an exceptionally dry February. In the West, Arizona recorded its second wettest January–February on record. New York and New Jersey had their wettest January on the books. In New York, this was followed by its second driest February; in North Carolina its third wettest January was followed by its third driest February. Despite the very dry February, New York still managed its second wettest December–February period on record because of excessive precipitation in December 1977 and January 1978. Other notable weather events during 1978 were the extremes of low pressure that were recorded in

January from the Mississippi River to the Appalachians and from Tennessee and western North Carolina to the Great Lakes. Record snowfall amounts were also recorded in southern New England during 1978.

The winter of 1979 produced a very cold December–January period in the western United States. Although the extreme cold weather moved to the eastern half of the United States in February, moderating temperatures from the Rockies westward, Colorado, Kansas, Missouri, Nebraska, Oklahoma and Wyoming had their coldest winter on record.

The state of Illinois was located within the −4.4°C (8°F) anomaly isopleth in each of these three severe winters. Remarkably, the three coldest winters on record for Illinois are 1978, 1979 and 1977, respectively. Snowfall reached record depths in Chicago during 1979, surpassing the record established during the previous season.

As Table 4 and Fig. 2c show, precipitation was generally plentiful over most of the nation during the 1979 winter season. In New York, 1979 and 1978 rank as the wettest and second wettest winters on record.

The consecutive occurrence of two record-setting cold winter seasons in the eastern United States has seen but few precedents in the historical meteorological record. The other severe back-to-back winters occurred in 1855–56/1856–57; and 1903–04/1904–05, and a series of cold winters were experienced in the 1880's. The occurrence in 1979 of yet a third severely cold winter (colder nationally than 1977 or 1978) provides us with the only record of such a happening in the instrumental meteorological record of the United States.

The severe winter weather of these past three winter seasons has been costly to this nation in terms of extra outlays for heating, transportation, lost wages, etc. In a study by Changnon (1979), it was estimated that in Illinois alone, the winter of 1978 brought about economic losses in excess of $1 billion.

3. Analysis of seasonal variability

In this section we present evidence that in recent years there has been a measurable increase in both monthly and seasonal temperature and precipitation variability.

Fig. 4 gives an areally-weighted index of monthly temperature and precipitation variability by consecutive 5-year periods, starting with January 1895, over the United States. The index was derived as follows:

1) Mean monthly temperature and precipitation values for the years 1895–1978 were used to calculate long-term monthly means and standard deviations for each state.

2) For each pentad during this period (through March 1979), the monthly means for each state were compared to the corresponding long-term monthly mean. Totals were accumulated for each state of the number of instances the monthly means fell beyond plus or minus one standard deviation ($\pm 1\sigma$) and, separately, plus or minus two standard deviation ($\pm 2\sigma$) limits.

3) The totals for each state were then multiplied by the state area weight (state area divided by total area of the 48 contiguous states) in order to accurately reflect the proportional contribution of each state to the total "national" variability.

4) These weighted totals were then summed over all the 48 states by pentad to produce the indices shown in Figs. 4a and 4b.

Fig. 4a shows the index values for variability of monthly mean temperature over the United States. While the frequency of the 1σ threshold is about average for the recent period, the frequency of anomalies exceeding $\pm 2\sigma$ is relatively large. Only the 1915–19 and 1930–34 pentads had higher totals.

Fig. 4b shows the corresponding index values for precipitation. As with temperature, the latest pentad shows an increase in extreme ($\pm 2\sigma$) precipitation variability compared to the past several pentads. Although the last nine months of 1979 are missing, this total is the third highest on record.

To give a measure of the statistical significance of the index values for the current pentad shown in Fig. 4, we calculated the mean and standard deviation of the 2σ temperature and precipitation index values. The corresponding averages (2.5 and 2.6, respectively, for precipitation and temperature) agree closely with what one might expect, considering that 60 is the maximum number possible and the expectation for a value greater than 2σ is slightly less than 5% of this total.

The index values for the 1975–79 pentad, which contains only 51 months, were more than 2σ from the mean for precipitation and over 1σ from the mean for temperature. Since this is an incomplete pentad, we adjusted the values proportionally to estimate the possible values at the end of 1979. These numbers were near 3σ from the mean for precipitation and 2σ for temperature.

The greater variability of monthly temperature exhibited in the past 5 years is also reflected in a sharp increase of winter temperature variability. Using winter-mean temperature averaged over the United States, standard deviations were computed over running 11-year intervals (curve in Fig. 5a). Points on the lines correspond to the central year of each 11-year period. The open circles

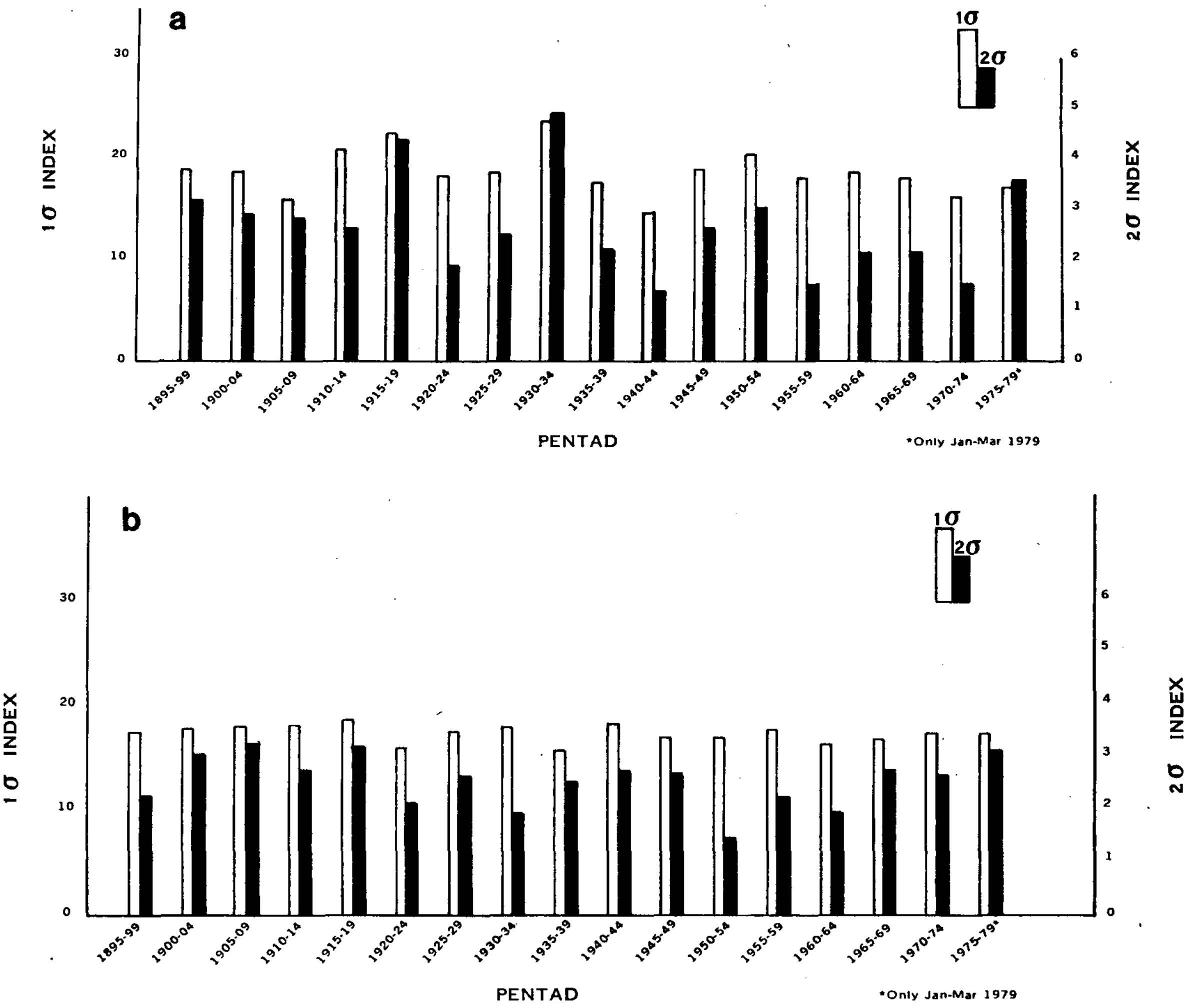


FIG. 4. Areally weighted nondimensional index of (a) monthly mean temperature variability and (b) monthly mean precipitation variability over the contiguous United States. Unshaded bar is for state monthly temperature and precipitation values exceeding ±1σ from the long-term mean; shaded bar is for values exceeding ±2σ from the mean.

are standard deviations computed over consecutive 5-year periods, and plotted at the beginning of each pentad. Although a general downward trend in standard deviation during the period since 1895 is evident from the graph, there is a clear upsurge during the past few years.

In order to show how this increased temperature variability was distributed over the United States, we performed the same computations for the East North Central (ENC) and Mountain (MT) regions of the United States. The ENC region comprises the states of Wisconsin, Michigan, Illinois, Indiana and Ohio; the MT region consists of Idaho, Montana, Wyoming, Utah, Colorado, Arizona and New Mexico. The results are shown in Figs. 5b and 5c. Although both regions show an increase in variability in recent years, the ENC region experienced a much larger increase in the 1970's; it also follows more closely the changes in the standard deviation of United States winter temperature (Fig. 5a), e.g., the increase in variance during the 1930's and the overall downward trend since the early part of this century. The Mountain region does not exhibit any significant long-term trend, but it shows a period of very high variability during the 1930's. Similar results were obtained by Chico and Sellers (1979), using a network of 79 stations in the United States.

To test the effectiveness of probability estimates of the occurrence of extreme winter temperatures such as occurred in 1977–79, the ENC region winter series was used to compute mean return periods for temperatures as cold or colder than those years. The ENC region was selected because, more than any other region of the United States, it experienced severe winter weather in each of the past three seasons. We initially applied the normal distribution to compute the probability of occurrence of a winter temperature as cold as that of 1977 using data through 1976; the calculations were repeated after including, first the 1977 value (to calculate the probability of a value as cold or colder than 1978), and then 1978 to calculate the probability for a 1979 value.

The results underscore the unusual character of the consecutive occurrence of these three severe winter seasons. Mean recurrence periods for temperatures as cold as those of the 1977, 1978 and 1979 seasons appeared to be too high (about 200, 95 and 85 years, respectively.) The probability of occurrence of three such events consecutively under the assumption of mutual independence is obviously implausible ($>10^4$ years).

Lag-correlation coefficients support the assumption of mutual independence to a good approximation (i.e., no significant correlation or periodicity is evident). The data also meet the randomness criteria. However, tests of normality using chi-square and kurtosis yielded ambivalent results (accept normality based on chi-square, reject based on kurtosis).

The Fisher-Tippett Type I extreme value distribution is often used to determine the cumulative probability function of the largest or smallest values occurring over arbitrary time periods (Gumbel, 1958). The cumulative extreme value distribution function can be written in the form

$$F(x) = F(x\colon \mu,\beta) = \exp(-e^{-y}), \qquad (1)$$

where $F(x)$ is the probability that an observation will be less than a specified value x, and y is a reduced variate defined as $y = (x - \mu)/\beta$, where μ is the mode of the distribution and β a scale parameter. In this case, since we are interested in the distribution of the "smallest elements", the negative of the above expression for y is used in place of y in (1). Estimation of extreme values for a specified probability level p can be accomplished from the relationship

$$\eta_p = \mu + \beta y_p. \qquad (2)$$

Confidence bands were determined on the assumption that the estimator η_p is normally distributed. Goodness-of-fit tests using chi-square and the Kolmogorov-Smirnov non-parametric test did not reject the extreme value distribution at the 5% level.

Although the individual winter temperature values are not extreme realizations of the random variate over a selected time period (i.e., only one seasonal

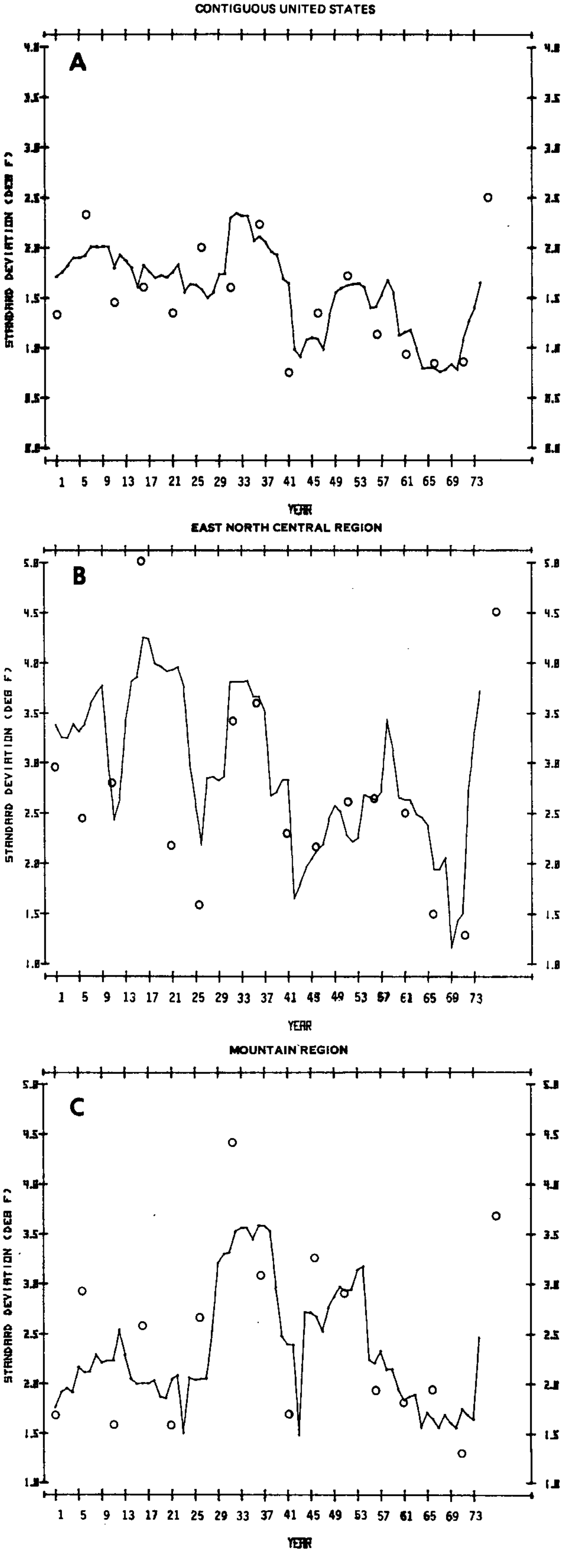


FIG. 5. Standard deviation (°F) of (a) US mean winter temperature, (b) ENC region mean winter temperature, and (c) mountain region mean winter temperature, computed over 11-year running intervals (1895/96–1978/79).

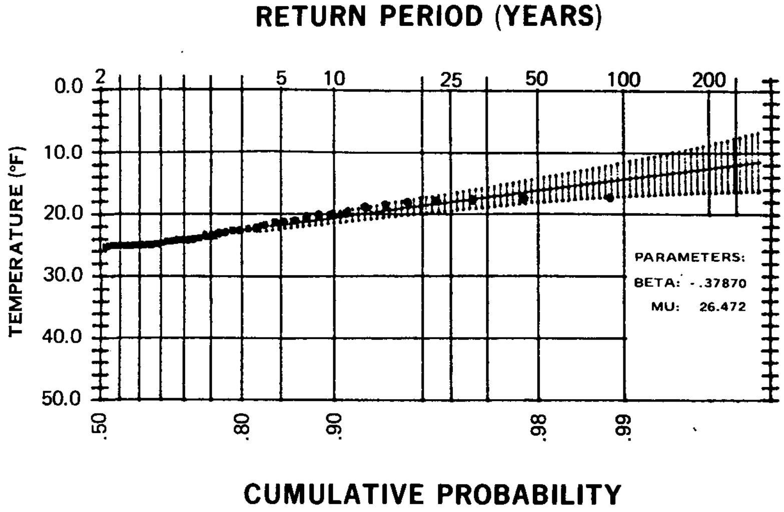


FIG. 6. Plot of the probability of occurrence and average return periods for ENC winter temperature. The shaded area is the 68% (±1σ) confidence region.

temperature is recorded each year), we nevertheless decided to fit the extreme value function to the seasonal data and test the model.

The mean return periods that were obtained appear quite reasonable. They were 91 years for 1977 (coldest value), and 29 and 18 years for the 1979 and 1978 values, respectively. Fig. 6 shows the model fit and one standard deviation confidence bands, with mean return period values from 2 to 200 years. Table 5 gives temperature values for selected return periods and the associated 95% confidence limits.

While the probability of occurrence of extremely low seasonal temperature equal to or less than the observed values is reasonable for individual outcomes, the probability of occurrence of three consecutive severe winters, such as were experienced in 1977–79 (assuming seasonal independence), is still implausibly low, having mean return periods on the order of 10^4 years.

Such extremely low probabilities for the occurrence of consecutive severe winters suggest that the development of large-scale anomalies in atmospheric circulation, which these low temperatures represent, may have a common dynamical forcing and that these forcing mechanisms possess time scales on the order of several years.

TABLE 5. Estimated values of East North Central region winter temperature (°F) for specified return periods.

Return period (years)	Temperature	95% confidence limits
25	18.0	15.3, 20.8
50	16.2	12.3, 20.1
100	14.3	8.8, 19.8
200	12.5	4.7, 20.3

A coupling mechanism has been proposed by Namias (1965, 1972, 1978b) involving large-scale atmosphere-ocean interactions. He suggests that recurrent circulation patterns may be due, initially, to the lifting of a deep reservoir of anomalously cool or warm subsurface water generated in antecedent seasons. In the zones of maximum temperature gradient, greater baroclinicity would lead to more frequent and intense cyclogenesis and to increased momentum transfer to the westerlies. Strong westerlies are generally associated with subsidence to the south of the zones of maximum winds, and thus with a tendency to increase surface pressures in the subsidence regions. This in turn could lead to the establishment of blocking patterns.

The development and refinement of a coupled atmosphere-ocean general circulation should provide insights and perhaps verification of the processes leading to the development and persistence of weather abnormalities at monthly and longer time scales.

4. Concluding remarks

We have shown that the occurrence of three consecutive severe winter seasons over the United States (1977–79) has no parallel in the modern historical record (since the 1890's). Many temperature records were set throughout the country during each of these three seasons. The core of the anomalous cold at the surface shifted westward in each succeeding season. This was related to a change in the orientation and strength of the ridge axis in 1978 compared with 1977 and a significant westward movement of the ridge-trough pair in the 1979 season.

January 1979 became the coldest month on record averaged over the contiguous United States, while January 1977 is the second coldest. Analysis of the probability of occurrence of such large temperature anomalies using normal and extreme value distribution models give mean return periods for individual events which are acceptable within rather broad confidence intervals, but which appear to be inadequate for estimating the probability of successive occurrences. This indicates a degree of seasonal persistence is present at times when large-scale atmospheric circulation anomalies develop.

Seasonal and monthly variance of temperature and precipitation has increased recently. Regionally this increase in variability has been concentrated in the eastern half of the country. The frequency of extreme temperature anomalies during the past five years is the highest since 1930–34 period and is the third highest 5-year frequency on record. The frequency of extreme precipitation anomalies over the past five years is the highest since 1915–19 period and is also the third highest total on record.

Extreme drought conditions in the western United States reached a peak during 1977, but ended decisively during the 1978 cold season when excessive precipitation helped replenish most of the region's reservoirs.

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