Planetary-Scale Forcing of the January 1977 Weather

Abstract. *The type of weather anomalies that occurred in the United States during January 1977 are typical of a planetary-scale wave phenomenon called stratospheric sudden warming (SSW). Specific changes in weather parameters nearly always accompany SSW. Blocking ridges (intensified high-pressure cells) develop over the oceans, the North Pole warms, mid-latitudes cool, and continental temperatures plunge. These characteristics usually persist for at least a month. When the SSW is strong, as in January 1958, 1963, and 1977, the accompanying weather anomalies can be unusually severe.*

Undoubtedly, much will be said and written concerning the weather conditions of January 1977. The unusual severity—of cold in the upper Midwest, the Great Lakes region, and the South; of snow in the Great Lakes region and throughout the East (and even in Miami and the Bahamas); of warmest-ever January temperatures in Alaska (bringing about the unseasonal budding of plants)—will cause January 1977 to be recorded as one of the most anomalous U.S. winter periods since quantitative records have been available. This period was also characterized by relative drought along the West Coast and throughout the West and Midwest and by gradually decreasing hemispheric temperatures; the events of January 1977 have contributed substantially to the drought and cooling and thus will probably also lead to speculation regarding climatic trends. Nevertheless, in at least one important respect, the flow patterns prevalent about and over the United States in January 1977 are typical of atmospheric events that have been observed repeatedly since the early 1950's. The conditions observed may simply be one of the more severe realizations of a type of phenomenon that occurs regularly in the atmosphere.

The principal points of this report are as follows: (i) the onset of severe weather conditions prevailing over the United States in January 1977 occurred simultaneously with a common, planetary-scale wave phenomenon called stratospheric sudden warming (SSW); (ii) important circulation anomalies in the lower atmosphere are associated with SSW; (iii) these anomalies are typified by major alterations in the atmospheric wave pattern throughout the hemisphere and by a major redistribution of surface temperature; and (iv) some modifications in wintertime storm development should accompany these anomalies.

In nearly 90 percent of all winters, the stratosphere (the atmosphere between approximately 12 and 55 km) experiences one major disturbance to its normal circulation pattern. From 1952, when SSW was first observed, until the present, approximately 55 percent of these disturbances have been observed to develop into SSW (*1–3*).

The wintertime stratospheric circulation above 20 km is dominated by a circumpolar vortex of strong westerly winds. During SSW, this vortex is broken up by a vertical propagation of energy from the lower atmosphere. The intensity of these events varies, but during strong SSW the strong westerly jet of about 80 m/sec is completely destroyed and localized heating of 80°C or more occurs in the upper levels of the polar stratosphere (above 30 km). During SSW, the troposphere (the atmosphere below approximately 12 km) undergoes circulation changes comparable in magnitude to those of the stratosphere (*2, 4–7*). The occurrence of stratospheric disturbances is related to anomalous decreases in the tropospheric energy content and to several other tropospheric circulation parameters (*2, 6–8*).

There is an almost complete one-to-one correspondence between major stratospheric disturbances and tropospheric energy decreases based on a continuous 9-year data set comprising five major SSW events and four lesser stratospheric disturbances (*2*). These decreases are qualitatively and quantitatively different from typical fluctuations in wintertime atmospheric energy parameters (*7–9*). The magnitude of these tropospheric energy disturbances increases with increasing intensity of the SSW (*7*). The strongest change in the energetics usually does not occur until after the SSW occurs (*2*). At the inception of an event, it is not always possible to predict whether the disturbance will become a SSW or only a minor event. The duration of the tropospheric disturbance is at least a month for SSW (*2, 7*). Of the approximately 14 SSW events observed since 1952, four have considerably exceeded the intensity of the remaining events, based on stratospheric circulation criteria. These four events occurred in January through February 1958 and January 1963, 1971, and 1977 (*1, 2*).

The most prominent change that occurs in the tropospheric circulation during SSW is an intensification and northward movement of the high-pressure cells, which are normally situated over the subtropical oceans. In all observed cases of SSW, intensified high-pressure cells, or ridges, developed either over the mid-latitude Pacific or Atlantic oceans or over both (*2, 4, 6, 8*). Starr (*6*) constructed the average height field for the 500-mbar pressure surface for 12 time periods during which the stratosphere was disturbed, including both major SSW and minor events. Figure 1 compares the average 500-mbar height field associated with a disturbed stratosphere with a climatological average January 500-mbar height field. In the average map typical for periods of stratospheric disturbances, the ridges over the Aleutian Islands and to the west of Spain stand out. These particular features in the height field are normally called blocking patterns because storms which develop upstream of them (to the west) tend to be deflected northward or south-

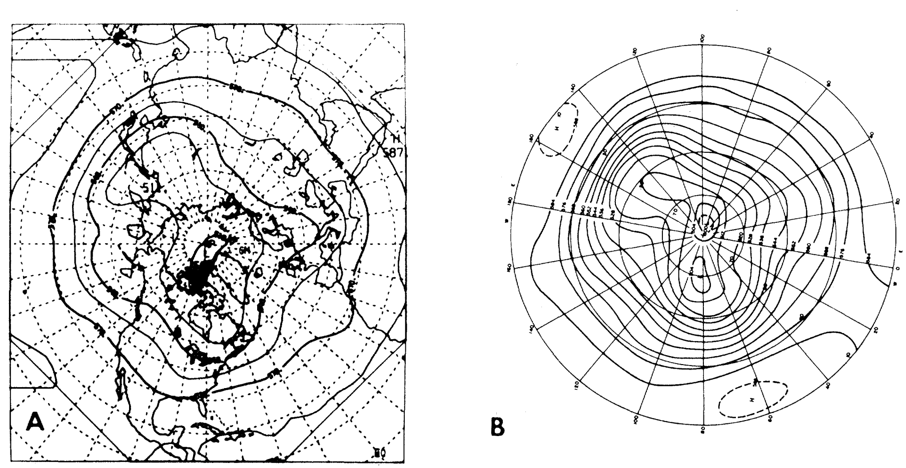

Fig. 1. (A) Mean 500-mbar height field (isoline spacing = 150 m) for 12 events of major stratospheric disturbance. (B) Climatological mean 500-mbar height field (isoline spacing = 80 m) for January (*6*).

ward so that the areas directly underneath and downstream of them are relatively storm-free. These blocking patterns are averaged over weak as well as strong stratospheric disturbances; moreover, the positions of the anomalous high-pressure cells are somewhat variable. Thus, the average map is a conservative estimate of the disturbance in the hemispheric height field.

Two individual examples of the 500-mbar height field during intense SSW are given in Fig. 2. In these height fields, the ridges extend to near or even across the North Pole. Also, during these two events the low center (at a height of approximately 4.94 km), which is normally located close to the pole, is displaced southward over Canada.

The average temperature of the atmosphere below 500 mbar at any point is approximately proportional to the height of the 500-mbar surface at that point. Therefore, the development of anomalously strong 500-mbar height gradients around a given latitude circle signals a change in the atmospheric temperature distribution around that latitude circle. Large amounts of warm air move northward under the anomalous 500-mbar

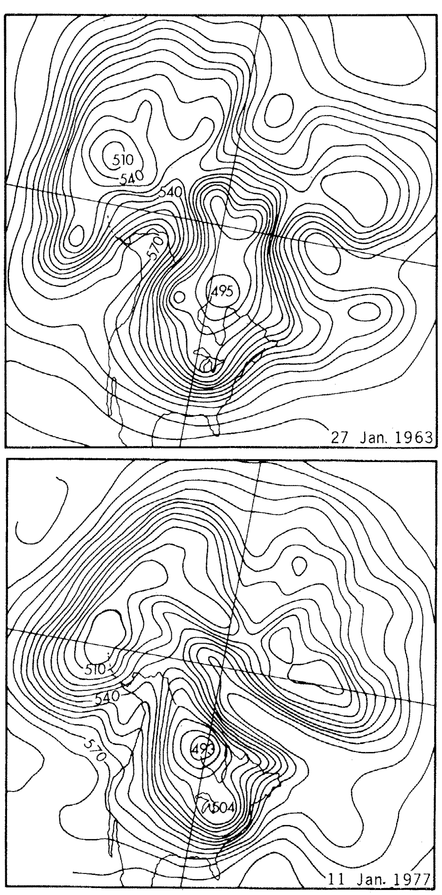

Fig. 2. The 500-mbar height fields for 27 January 1963 and 11 January 1977 (isoline spacing = 60 m).

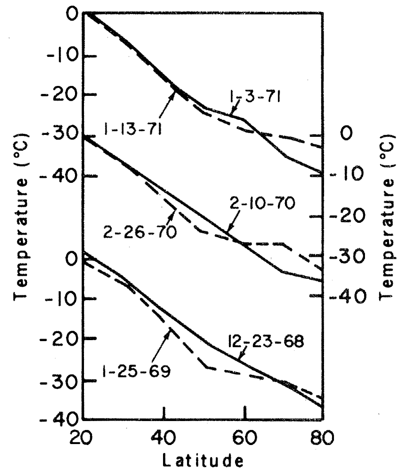

Fig. 3. Mean meridional temperature profiles for the 1000- to 300-mbar layer for typical days preceding (solid lines) and during (dashed lines) three SSW events.

ridges, and as a result rapid temperature increases occur even over the pole. Similarly, very cold air under the 500-mbar lows moves southward. Because the highs develop preferentially over the oceans and lows over continents during SSW, cold air will predominate over continents. In fact, through most of the mid-latitudes, average tropospheric temperatures decrease (2). Figure 3 shows vertically and latitudinally averaged meridional temperature profiles for the atmosphere below 300 mbar for three SSW events. The observed cooling between latitudes 40°N and 60°N is apparent as is the warming over the pole.

To substantiate the expected cooling over continents during SSW, the monthly mean temperatures (MMT's) of 28 stations distributed throughout the United States were examined. I computed the means and standard deviations (σ) of the MMT's, using 15 years of data, excluding years with strong SSW. Then I compared the four strong SSW periods with the base-line data set to determine if the MMT's of the four SSW periods were statistically different from base-line values. If a normal distribution of the MMT about its climatological mean is assumed, the average MMT's for the four intense SSW at eight stations were statistically different from their base-line MMT's (t-test, $P < .01$). A total of 15 of the 28 stations had average MMT's during SSW which differed statistically from the climatological mean ($P < .05$); these 15 stations were located exclusively in the Midwest, the South, and the East. For the four events, an average of 74 percent of the stations possessed negative anomalies (lower than normal temperatures) and the average negative anomaly, which varied between 2.2° and 4.8°C for different stations, amounted to 1.5 σ. The MMT at only one station outside of the Pacific Northwest and the Southwest was insignificantly different statistically from the base line. Thus the eastern two-thirds of the United States may be expected to cool by a large amount (approximately 1.8° to 4.2°C) and with considerable regularity ($P < .05$) after the onset of SSW. In fact, even those stations in the West having MMT's for the four SSW relatively close to their climatological MMT show the effects of SSW. The average of the absolute values of the anomalies at western stations during SSW is 1.2 σ; that is, depending rather sensitively on the exact position of intensified high-pressure cells over the Pacific, the West and Southwest will lie in a region of either large positive or large negative MMT anomalies.

It is thus apparent that SSW is accompanied by major tropospheric adjustments that modify surface weather. The intensification and movement of high-pressure cells over the ocean should affect storm track positions and the sources of air masses which pass over specific locations. This shift in air mass source leads to dramatic temperature depressions over large continental areas. Thus during January 1977, only two of the 28 stations examined throughout the continental United States experienced MMT's above normal: San Diego, California, and Olympia, Washington. As the SSW develops and the cold air moves southward over the continents, extreme temperature depressions are observed, far in excess of the MMT anomalies. Fig-

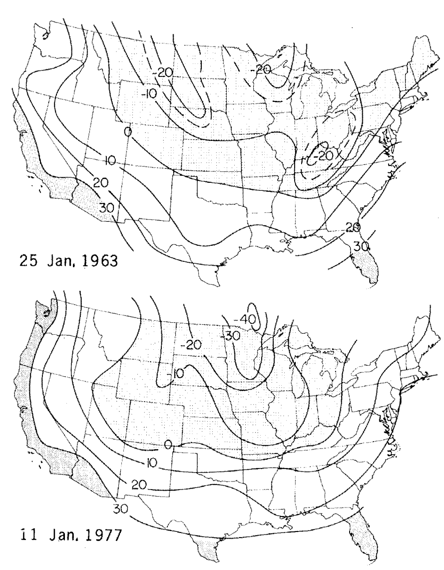

Fig. 4. Nighttime minimum temperature pattern (in degrees Fahrenheit) for 25 January 1963 and 11 January 1977. Heavy shading shows areas above 32°F and light shading areas below 0°F.

ure 4 shows the temperature pattern for 2 days during the 1963 and 1977 SSW in which the nightly minimum temperature remained above freezing over only a small part of the United States.

Another effect, not discussed here, results from large modifications in the atmospheric energy cycle. During SSW a large portion of the energy available for storm development is lost to the stratosphere and to space (up to 60 percent of the annual variation of this energy) (*7*). With such a dearth of energy for storm development, a reduction or at least a modification in storm activity is anticipated. However, the magnitude of this reduction as well as the change in the average storm track position, are difficult to substantiate statistically on the basis of the relatively few strong SSW presently available for study.

At any rate, weather over the United States is remarkably similar during strong SSW, as shown by the weather summaries prepared by the National Weather Service for 1958 and 1963 (*10*). These descriptions of snow in the upper Midwest and Florida, warm weather in Alaska, dryness in the West, and persistent cold east of the Rockies were repeated in the January 1977 weather. Therefore, the extreme conditions of January 1977 seem to be typical of strong SSW and thus they should not be considered all that rare.

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Nitrous Oxide: Emission from Soils During Nitrification of Fertilizer Nitrogen

Abstract. *Nitrous oxide is released from soils to the atmosphere during nitrification of ammonium and ammonium-producing fertilizers under aerobic conditions as well as by denitrification of nitrate under anaerobic conditions. Emissions of nitrous oxide during nitrification of fertilizer nitrogen may be significant in regard to the potential threat of fertilizer-derived nitrous oxide to the stratospheric ozone layer. Such emissions can be greatly reduced through the use of nitrapyrin, which inhibits nitrification of ammonium by soil microorganisms.*

Recent literature reflects international concern that increased use of fertilizer N to aid world food production may pose a threat to the stratospheric O_3 layer (*1–3*). This concern stems from the hypothesis that N_2O released to the atmosphere through denitrification of fertilizer-derived nitrate in soils may trigger reactions in the stratosphere leading to partial destruction of the O_3 layer (*2, 4*).

Most of the fertilizer N now added to soils is in the form of ammonium or of urea, which is rapidly hydrolyzed by soil urease with the formation of $(NH_4)_2CO_3$. This N is not susceptible to denitrification until it is nitrified, that is, oxidized to nitrite or nitrate by soil microorganisms. Although there is evidence that heterotrophic microorganisms may contribute to the nitrification of ammonium in soils (*5*), it is generally believed that autotrophic bacteria (species of *Nitrosomonas* and *Nitrobacter*) are largely responsible for nitrification in soils and other natural ecosystems (*6*). *Nitrosomonas* sp. oxidize ammonium to nitrite, and *Nitrobacter* sp. oxidize nitrite to nitrate.

There is abundant evidence that N_2O is released from soils through denitrification of nitrate under anaerobic conditions. We report here evidence that this gas also is released from soils during nitrification of ammonium under aerobic conditions.

The possibility that N_2O may be released to the atmosphere during nitrification of fertilizer N was studied because several workers have detected formation of small amounts of N_2O during the oxidation of ammonium by intact cells or cell-free extracts of *Nitrosomonas europaea* under certain conditions (*7*). To investigate this possibility, we studied the release of N_2O from soils incubated under aerobic conditions after treatment with different forms of fertilizer N. The soils were surface (0 to 30 cm) samples of Iowa soils used for corn and soybean production. They were sieved (2-mm screen) in the field-moist condition, and samples of the screened soils containing 30 g of oven-dry material were incubated at 30°C for various times after treatment with different forms of N and sufficient water to bring their water content to about 60 percent of the water-holding capacity. Incubations were carried out in 1.2-liter bottles sealed with glass stoppers fitted with a ground-glass joint and a glass stopcock. The atmospheres in the bottles were sampled at 2-day intervals for determination of N_2O and O_2 by gas chromatography (*8*), and the bottles were aerated for a few minutes immediately after these determinations. The O_2 determinations showed that the atmospheres analyzed always contained at least 20 percent O_2 (by volume).

Table 1 shows that the amounts of N_2O released from well-aerated soils treated with $(NH_4)_2SO_4$ or urea were much greater than the amounts released from soils treated with KNO_3 (*9*). Whereas the amounts of N_2O released from soils treated with $(NH_4)_2SO_4$ or urea increased with the amount of ammonium N or urea N added, the amounts of N_2O released from soils treated with KNO_3 did not increase significantly with the amount of nitrate N added and were not appreciably different from the amounts released from unamended soils. This result indicates that very little, if any, of the N_2O released from the soils treated with $(NH_4)_2SO_4$ or urea was produced through denitrification of nitrate. Evidence that the observed emissions of N_2O resulted from microbial activity was obtained from experiments showing that no release of N_2O could be detected when soils sterilized by autoclaving at 120°C for 2 hours were incubated under aerobic conditions at 30°C after treatment with N as $(NH_4)_2SO_4$ or urea (100 μg of N per gram of soil).

The deduction from Table 1 that N_2O is produced during nitrification of ammonium N or urea N in soils under aerobic conditions is supported by our finding (Table 2) that nitrapyrin [2-chloro-6-(trichloromethyl)pyridine] greatly reduces the emission of N_2O from well-aerated soils treated with $(NH_4)_2SO_4$ or urea. We studied the effect of nitrapyrin because this compound inhibits the oxidation of ammonium to nitrite by *N. europaea* (*10*)

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