The sudden breakdown of an unusually strong cyclone in the stratosphere during winter 1988/89

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SUMMARY

In February 1989, a dramatic major warming occurred in the stratosphere of the northern hemisphere after an unusually cold January. The stratospheric westerly vortex was split when an anticyclone developed over Europe, apparently in response to cyclogenesis upstream in the troposphere. At the peak of the warming, the circulation resembled that of the warming of February 1979, save for a rotation of flow patterns. Very low temperatures in the lower stratosphere before the warming indicate that polar stratospheric clouds were present, so that heterogeneous chemical reactions with the potential for ozone destruction may have taken place.

1. INTRODUCTION

Concern over the rapid destruction of ozone in the lower stratosphere above Antarctica during the Austral spring has prompted renewed interest in the meteorology of the polar stratosphere in both hemispheres. The circulation in the northern hemisphere stratosphere during winter 1988/89 is of particular interest because a major international mission (the Arctic Airborne Ozone Experiment (AAOE)) was conducted at that time to determine whether the anomalous chemical and meteorological conditions found to favour ozone destruction over Antarctica were reproduced over the Arctic.

In this paper, we draw attention to the evolution of the stratospheric circulation during January and February 1989. We focus on a dramatic major warming which occurred in the stratosphere in February. During this event, the westerly (eastward) flow of winter was broken down, and temperatures rose by more than 50 degC in ten days over the polar cap. The warming was even more striking because it followed the coldest January on record in the northern hemisphere stratosphere. We base our discussion on the warming on measurements from a polar-orbiting satellite. Such measurements afford a near-global, three-dimensional view with good coverage in time and space.

A curious feature of the warming, meriting further study, was its resemblance to the well-known major warming of February 1979. At the peak of the warming the circulation was remarkably similar to that of 1979, save for a simple rotation of the flow pattern about the north pole. This similarity applied through a large depth of the stratosphere, and was all the more intriguing because the flow patterns were not simple (e.g. they could not be well represented by the zonally averaged (rotationally symmetric) flow plus a single zonal harmonic).

In comparing the warmings, we make tentative connections between localized developments in the troposphere and the development of stratospheric features. Cyclogenesis in the upper troposphere and lower stratosphere over North America appeared crucial to the evolution of both warmings.

We argue that, unlike the flow in early February 1979, the stratospheric circulation before the major warming of 1989 cannot be described as ‘preconditioned’, in the sense in which the term was used by Kanzawa (1980) or McIntyre and Palmer (1983). The westerly vortex was large, deep and cold before the warming, and the zonal-mean jet correspondingly broad and strong.

Low temperatures in the lower stratosphere during January strongly suggest the presence of polar stratospheric clouds (PSCs) over the Arctic polar cap. PSCs are thought to play an important role in the formation of the ‘ozone hole’ over Antarctica (Solomon 1988). An important question, currently under intense investigation by those involved in the AAOE mission, is whether or not PSCs have a comparable role over the Arctic. Our analyses have some bearing on this question.

2. DATA AND METHOD OF ANALYSIS

Our analysis is based on measurements from stratospheric sounding units (SSUs) on board the NOAA operational satellites NOAA-11, for 1989, and TIROS-N, for 1979. The SSU normally

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makes radiometric measurements in three channels with weighting functions centred at 15, 5 and 1.5 mb (1 mb equals 1 hPa)—channels 25, 26 and 27 respectively—though for 1979, channel 27 was inoperative. Layer thicknesses are derived for the stratosphere by the method outlined by Clough et al. (1985). Although radiances from the SSU have the biggest impact on these fields, measurements from a microwave sounding unit (MSU) and from a high-resolution, infrared sounder (HIRS-2) on board NOAA-11 contribute to the analysis for 1989. (Pick and Brownscombe 1981 give further details of these instruments.) Daily fields of geopotential height for isobaric surfaces in the stratosphere are then constructed by adding the thicknesses to the field of geopotential height at 100 mb. For 1979, the 100 mb field is an objective analysis made by the European Centre for Medium Range Weather Forecasts; for 1989, it comes from the Meteorological Office.

3. Description of the major warming of 1989

The major warming of February 1989 followed the coldest January in 25 years in the stratosphere of the northern hemisphere. Kuhlbransch and Naujokat (1989) found temperatures as low as −92°C locally at 30 mb, and in our analyses of SSU measurements, temperatures fell below −70°C over the polar cap at 10 mb in mid January. Associated with these record low temperatures was an intense cyclonic vortex. Figure 1(a) shows the evolution of the zonal-mean wind in the middle stratosphere from 1 April 1988 through to 31 March 1989. Winter westerlies intensified strongly in December 1988 and by mid January they reached 80 m s$^{-1}$ at 60°N. At the end of January, there was a short-term reduction in the wind speed associated with a brief minor warming. This was followed, in early February, by a rapid deceleration of the winds, in association with an equally dramatic rise in polar temperature of more than 50 degC in ten days (Fig. 1(b)). By the end of February, zonal-mean easterlies were present poleward of 60°N, at and above 10 mb. The warming thus satisfied the commonly accepted (WMO) criterion for major warmings.

We now turn to synoptic maps for the stratosphere to examine the evolution of the major warming of 1989 in more detail. In making tentative connections with the troposphere, we refer to maps at 100 mb in the lower stratosphere. As is generally the case, the flow at 100 mb looks like a smoothed version of the large-scale flow in the upper troposphere.

Figure 2 shows the fields of geopotential height at 10 and 100 mb on 28 January 1989, at the peak of the minor warming. The flow at 10 mb comprised a large, cold cyclone and a warm anticyclone called the Aleutian high. These features are characteristic of the mid winter circulation in the stratosphere in the northern hemisphere. O'Neill and Pope (1988) suggested that the Aleutian high is primarily a downstream response of the stratosphere to a climatological feature, the East Asian low, in the troposphere. In accord with this suggestion, there was a well-marked trough at 100 mb over East Asia on 28 January.

In early February, cyclogenesis occurred in the upper troposphere and lower stratosphere over North America. In Fig. 3, for 12 February, a closed cyclonic circulation extended from the lower to the middle stratosphere. Apparently as an upward and downstream response to this cyclogenesis, an intense, quasi-stationary anticyclone developed over Europe. This feature became the dominant anticyclone in the middle stratosphere, consistent with the upstream location of the dominant trough in the upper troposphere and lower stratosphere.

As the European anticyclone intensified in the stratosphere, the cyclone became more and more elongated, and eventually split in two. Figures 4 (a) and (b) show fields of geopotential height in the middle and lower stratosphere for 19 February. There were four distinct vortices in the middle stratosphere—two cyclones and two anticyclones. Zonal wavenumber 2 had the largest amplitude in the height field at 10 mb, but the flow cannot be adequately represented by a simple superposition of wave 2 on a zonal-mean flow. Matching pairs of vortices had unequal intensity and (as noted below) very different vertical structures.

Near the entrance to the southerly jet which formed over the North Atlantic between the stronger cyclone and anticyclone, there was a rapid increase in temperature. In an analysis of the major warming of winter 1984/85, Fairlie et al. (1990) identified strong descent and adiabatic warming in such a region, where sinking motion augments the horizontal motion in tightening the horizontal temperature gradient. A map of SSU brightness temperature for 19 February (Fig. 4(c)) shows a single pool of warm air stretching from north-east Canada across the polar cap. At the entrance to the southerly jet between the weaker cyclone and anticyclone, the warming was less intense and no distinct warm pool of air was formed. Consistent with this temperature pattern, the stronger cyclone tilted westward with height in the lower and middle stratosphere, while the weaker had almost no tilt.
Figure 1. (a) Zonal-mean, geostrophic wind at 10 mb in the northern hemisphere for the period April 1988 through to March 1989. Contours are plotted at intervals of 5 m s\(^{-1}\), and shading denotes easterly winds. (b) Zonal-mean temperature (°C) at 85°N and 10 mb for January and February 1989.

After the breakup of the flow into distinct vortices, the evolution of the circulation became much more complicated, and is not described here. Instead, we now compare the flow and temperature fields portrayed in Fig. 4 with those at the peak of the major warming of February 1979.

4. **Comparison with the Major Warming of February 1979**

There was one striking difference between the evolutions of the major warmings of February 1979 and 1989. In 1989, the warming was the first major disturbance to affect the stratospheric circulation in winter. Consequently, polar latitudes were particularly cold and the westerly vortex especially large and strong before the warming (see earlier discussion). In 1979, on the other hand, the major warming followed a strong minor warming at the end of January, which left the vortex much smaller and the circulation considerably weaker than in February 1989.

Despite this difference, the warmings had some notable elements in common. Both evolved from asymmetric flow fields, characterized by a displaced and elongated polar cyclone and an
Aleutian anticyclone (Fig. 9(e) of Palmer and Hsu 1983 shows a map for 7 February 1979). Cyclogenesis in the upper troposphere and lower stratosphere over North America and the development of a ridge downstream in the stratosphere were features of the 1979 warming as well as that of 1989. Unlike 1989, however, in 1979 the East Asian low remained the dominant tropospheric cyclone and the Aleutian high the dominant stratospheric anticyclone.

As a result, when the polar vortex was split at the peak of each warming, the flow fields in the lower stratosphere and upper troposphere were similar, but for a simple rotation of the patterns about the north pole. Figures 5(a) and (b) show fields of geopotential height, and Fig. 5(c) a field of brightness temperature for 22 February 1979. The fields have been rotated clockwise by 150° with respect to the synoptic maps shown in Fig. 4, with which they are to be compared. First, in both cases, the more intense (and colder) cyclone lies to the left, above the stronger of the two troughs in the lower stratosphere. Second, the stronger of the two anticyclones (in the case of 1979 (Fig. 5), the single closed anticyclone), lies directly downstream. Third, a single warm tongue of air lies along the southerly jet that had formed between these two vortices. Consequently, the stronger cyclone tilts westward with height; the other cyclone does not.

5. POLAR STRATOSPHERIC CLOUDS

January 1989 was the coldest on record in the stratosphere of the northern hemisphere (see above discussion). In Fig. 6, we compare temperatures in the lower stratosphere during December and January 1988/89 with those from other years. The dashed line represents a time series of minimum temperature in the lower stratosphere for 1988/89. The solid lines define an envelope of such curves for the years 1980 through to the winter of 1989. The temperatures were obtained from measurements made in channel 24 (centred near 90 mb) by microwave sounding units on board NOAA operational satellites (see Pick and Brownscombe 1981 for details of the MSU). At the end of January, the minimum temperature fell to −83°C, cold enough (less than about −76°C) for type 1 PSCs (solid, binary, nitric acid/water clouds) to form at these levels (McCormick and
Figure 4. (a) and (b). As for Fig. 2 but for 19 February 1989. (c) Synoptic map of SSU channel 25 brightness temperature (°C) for 19 February 1989. Channel 25 is centred near 15 mb. Contours are plotted at intervals of 2 degC.

Figure 5. Synoptic maps of geopotential height (dam) at (a) 10 and (b) 100 mb for 22 February 1979. (c) Synoptic map of SSU channel 25 brightness temperature (°C) for 22 February 1979. The maps in Fig. 5 have been rotated clockwise by 150° with respect to those in Fig. 4.
Figure 6. Minimum brightness temperature (°C) as a function of time, measured by MSU channel 24 in the northern hemisphere for the period December through to May. The dashed curve is for 1988/89. The full lines form the envelope of such curves for years 1980 through to the winter of 1989. Channel 24 is centred near 90 mb.

Poole, personal communication) and even for type 2 'ice' clouds to form (Hanson and Mauersberger 1988). These clouds have been implicated in anomalous chemical reactions which lead to the rapid destruction of ozone over Antarctica during the Austral spring (Solomon 1988). Temperatures from the MSU suggest that PSCs may have covered the polar cap north of about 75°N for about 10 days in mid January (the presence of local pockets of PSCs farther south is not excluded by the measurements, owing to their limited resolution). McCormick and Poole (personal communication) have inferred the presence of ice clouds as far south as about 70°N, using measurements from the SAM II instrument on board the satellite Nimbus-7. (McCormick et al. 1979, give details about SAM II.) Figure 6 shows that in early February minimum temperatures in the lower stratosphere rose rapidly above −76°C, and, presumably, PSCs disappeared almost everywhere. (Measurements from SAM II confirm the disappearance of the clouds.)

MSU measurements indicate that the area covered by PSCs over the Arctic is much smaller and their duration shorter than over the Antarctic, where PSCs may cover the polar cap down to about 68°S for up to two months in winter. On the basis of cloud coverage and duration alone, one might therefore expect PSCs to have a much smaller impact on stratospheric chemistry in the northern winter than in the southern. So far, there have been no reports of dramatic ozone destruction during springtime in the northern hemisphere. But because of the unusual meteorological conditions during early 1989—a very cold January, followed by a sudden warming in February—the circulation during these months should not be regard as typical. There continues to be a need to monitor closely, changing conditions in the winter stratosphere of both hemispheres.

6. DISCUSSION

The major warming of February 1989 evolved in three to four weeks, following the coldest January on record. Before the period of rapid zonal-mean deceleration, the stratospheric cyclone was large and deep (Fig. 2) and the zonal-mean jet broad and strong (Fig. 1). Hence, the circulation should not be viewed as 'preconditioned' for the major warming in the sense in which the term was used by Kanzawa (1980) or McIntyre and Palmer (1983). (McIntyre and Palmer, for example, predicted that the cyclone would be 'unusually small' before a major warming.) Nor is the warming of February 1989 exceptional in this respect. Fairlie and O'Neill (1988) found a similar result in their study of the major warming of January 1985. They pointed out that the warming of February 1979, upon which McIntyre and Palmer based their ideas about preconditioning, was unusual in having a small vortex before the breakdown.

In describing the major warming of February 1989, we make tentative connections between the development of stratospheric features and local developments in the troposphere. Specifically, we suggest that the development of a quasi-stationary anticyclone in the stratosphere over Europe was associated with cyclogenesis in the troposphere over North America. The connection is analogous to that which is thought to exist between the Aleutian high and the tropospheric East Asian low (O'Neill and Pope 1988). Other cases provide more evidence of a connection. Besides
the warming of February 1979, discussed above, quasi-stationary anticyclones developed over the North Atlantic during the wave 2 warmings of January 1982 and winter 1984/85 (Fairlie and O’Neill 1988), following cyclogenesis over North America.

The above-mentioned connection between local developments in the troposphere and stratosphere must be regarded as a tentative suggestion based on empirical evidence. A local connection cannot be established with certainty for the following reasons. First, cyclogenesis in the troposphere takes place over a finite time (about a week), during which there is likely to be a downstream influence in the troposphere as well as in the stratosphere. For example, a downstream ridge may develop (as part of a Rossby wavetrain), leading perhaps to a blocking anticyclone and further impact on the stratosphere. Second, localized cyclogenesis may be governed by the structure of the flow on a larger scale. Third, the stratosphere may respond in a nonlinear fashion to large-amplitude tropospheric disturbances, precluding a one-to-one connection between tropospheric and stratospheric events (O’Neill and Pope 1988).

In February 1989, cyclogenesis and the development of a second anticyclone in an already distorted flow was manifested in Fourier space as a transition from wave 1 to wave 2 in geopotential height, over a deep layer of the stratosphere and upper troposphere. Fairlie and O’Neill (1988) showed evidence for a nonlinear coupling between the harmonics during a similar transition from wave 1 to wave 2 in December 1984. Actual wave 2 warmings (and wave 1 warmings, for that matter) do not evolve on a time-scale of a week or so from an axisymmetric state (about the pole or any other axis), upon which a wave 2 disturbance develops coherently. Indeed, in some cases, it is a misnomer to call these events ‘wave 2 warmings’. At the peak of the major warmings of 1979 and 1989, the thermal pattern was characterized by a single warm pool and the two parts of the split cyclonic vortex had quite different vertical structures. These points should be borne in mind in designing idealized experiments to explore the dynamics of sudden warmings.

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REFERENCES


