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Ozone loss in middle latitudes and the role of the Arctic polar vortex

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There have been a number of different suggestions as to the cause of the observed ozone decline over middle latitudes. Here, the particular impact of polar processes on the middle latitude lower stratosphere is discussed. Recent studies suggest that air, recently activated and then torn from the edge of the polar vortex, contributes to the observed ozone decrease. For example, observational and modelling studies both indicate that there is an important role for filaments of vortex air being stripped away from the vortex edge. However, there appears to be little support for the idea of the vortex as a massive 'flowing processor' through which large quantities of air, primed for ozone destruction, are transported.

1. Introduction

The cause of polar ozone depletion is now reasonably well understood: at low temperatures in the winter polar lower stratosphere, polar stratospheric clouds (PSCs) form. Reactions on the surface of the PSCs turn chlorine compounds from inactive forms (e.g. HCl, $ClONO_2$) into active forms (e.g. ClO) which, in the presence of sunlight, destroy ozone.

Much more controversial is the cause of the decline in ozone in middle latitudes of the Northern Hemisphere, amounting to about 4% per decade (annual average) since 1979 (WMO 1995). Most theories implicate the halogen compounds but the precise details of the processes involved remain in dispute. One possibility is that the ozone depletion occurs in polar latitudes and this air is then mixed into middle latitudes causing a general 'dilution' of ozone levels there. A second possibility is that air is primed for ozone depletion by the reactions on PSCs in polar regions, but is then transported southward, and possibly mixed, before the depletion occurs. If this process operates continuously (like a 'flowing processor', see McIntyre (this volume)) then large ozone loss might occur in mid-latitudes. A further possibility is that the chlorine is activated *in situ* in middle latitudes, possibly on sulphate aerosol, followed by local ozone depletion.

It is clearly important to establish quantitatively the degree of mixing between the polar vortex and lower latitudes. Large, rapid flow through the polar vortex has the potential to carry air to middle latitudes which could produce significant *in situ* ozone depletion. Furthermore, this process would itself be one of the major factors determining the chemical structure of the middle latitude lower stratosphere (and, incidentally, would imply that previous assessments using two-dimensional models of,

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for example, the impact of aircraft on the lower stratosphere could be considerably in error).

There has been an energetic debate with a spectrum of views, ranging from the idea of the vortex as a continuous 'flowing processor' to the idea that the vortex is highly isolated and only mixes with middle latitudes (leading to 'dilution') at the time of the final warming. Unfortunately, the debate has been hampered by inadequate, and often differing, definitions of what is meant by the edge of the polar vortex, and so on. Nevertheless, there is a surprisingly large amount of objective agreement to be found in the literature. Many studies indicate that there can be considerable exchange between the edge of the vortex, where air can be chemically processed, and middle latitudes.

It is clearly of importance that quantitative studies of the extent of mixing are carried out using independent datasets, including some of the global fields available from the upper atmosphere research satellite (UARS). Special attention should also be paid to the region below 400 K which is generally more difficult to observe from space and is not probed so effectively by *in situ* aircraft measurements.

In the next section we summarize some data and modelling studies which have discussed the impact of polar processes on middle latitudes.

2. The impact of polar processes on middle latitudes

A number of studies using data, models, and a combination of both data and models have been carried out to investigate the extent to which air is mixed between the polar vortex and middle latitudes. Many of these have concentrated on the arctic vortex, studied extensively in the polar campaigns: the European Arctic stratospheric ozone experiment (EASOE); the second European stratospheric Arctic and middle latitude experiment (SESAME) and the airborne Arctic stratospheric expedition II (AASE II). Studies using UARS data have also appeared.

The results from some of these studies are presented below. The studies chosen all show mixing, to a greater or lesser extent, but none support the idea of a large and continuous flow through the polar vortex.

The erosion at the vortex edge has been demonstrated quite beautifully in a number of new studies using the technique of contour advection with surgery (Norton 1993; Waugh 1993; Plumb *et al.* 1994). Results from these studies show thin filaments being dragged around the vortex edge and being carried into middle latitudes. Interesting examples were reported during a disturbed period in January 1992. These results are consistent with the large scale potential vorticity (PV) maps of the Northern Hemisphere, but reveal structure on small scales which is only hinted at in a tantalising fashion in the meteorological analyses. That some of the structure is indeed real has been demonstrated by the very elegant four-dimensional variational assimilation work of Fisher *et al.* (1993).

Large scale model calculations are also consistent with these results. For example, Rood *et al.* (1992), Chipperfield *et al.* (1994) and Chipperfield (1994) have all described studies in transport models using analysed wind and temperature fields. Rood *et al.* (1992) conclude that intense cyclonic activity close to the vortex edge and large planetary scale events are the major mechanisms of extra-vortex transport. Nevertheless, in their study of a disturbed period in January and February 1989, only a small amount of processed air is found outside the polar vortex.

Chipperfield (1994) has studied the Arctic winters of 1991/92 and 1922/93. He considered the distribution of a model tracer, which records the number of hours of sunlight experienced by an air parcel which has also seen PSC temperatures within the previous 14 sunlight-days. The tracer contains the two conditions necessary for rapid ozone loss, PSC processing (to convert chlorine species to ClO) and exposure to sunlight (to enable the catalytic ozone destruction cycles to operate). Most of the modelled tracer is found well within the polar vortex but there is a considerable amount of tracer at about 160° E in a region of lower PV moving away from the vortex edge. A chemical model for the same period shows elevated ClO in this same region (Chipperfield *et al.* 1994). These results are in extremely good qualitative agreement with the contour advection results presented by Plumb *et al.* (1994). Thus, like the Rood *et al.* (1992) study, this model also shows mixing at the vortex edge. Despite being run for rather disturbed dynamical periods, neither model shows a large degree of continuous vortex to extra-vortex transport.

A number of other trajectory studies of the Northern Hemisphere support these conclusions. MacKenzie *et al.* (1994) looked at ensembles of isentropic trajectories, appropriately labelled if PSC conditions had been encountered within the previous 20 days. For both 1988/89 and 1991/92 they show that the midwinter vortex was filled with air which had been PSC-processed. Outside the vortex, they also found examples of processed air. However, in all these cases the active temperatures had been encountered at PV values characteristic of the vortex edge. They found no evidence of air having been ejected from the centre of the vortex.

Pyle *et al.* (1994) have carried out a case study of mid January 1992 during which adiabatic cooling in the stratosphere between Greenland and northwest Europe led to a large region favourable for PSC formation on and near the edge of the polar vortex. Using winds from a high resolution GCM integration initialized on 18 January, a large number of trajectories were started covering the area of low temperatures. Most of the trajectories remained close to the vortex edge, but a substantial number of air parcels were found away from the vortex at around 45° N close to the Caspian Sea, coincident with a region of high PV in the meteorological analyses for the same day. It seems clear that the feature is real, and at least in part arises from vortex erosion, probably exceptionally strong erosion in view of the exceptionally strong disturbance to the vortex.

In order to investigate the associated chemistry in more detail, a chemical package was integrated along a subset of the trajectories. For those trajectories staying close to the vortex edge, ozone depletions of around 1% over ten days were calculated. For the trajectories that moved to lower latitudes, a depletion of the order of 1% per day was calculated. It is clear that middle latitude depletion can arise from this process.

The studies discussed above have generally concentrated on relatively short periods or specific synoptic situations. In an attempt to draw some more general conclusions, Dahlberg & Bowman (1994) have carried out isentropic trajectory studies for nine northern hemispheres. Their conclusions, in broad agreement with the above, is that a barrier inhibiting mixing typically forms near the vortex boundary and is strongest in January and February. At 450 K the transport that does occur across the barrier is predominantly in the form of thin filaments ejected from the vortex. In December and March the mixing barrier is weaker due to non-conservative factors during the spin-up and breakdown (leading to dilution) of the vortex, respectively.

A number of these studies have also discussed occasions on which air is mixed from outside into the vortex. For example, Plumb *et al.* (1994) show evidence for transport into the Arctic vortex in January 1992, a case also mentioned by Pyle *et* *al.* (1994). In addition, Dahlberg & Bowman (1994) give a number of examples of poleward mixing, but indicate that these cases are generally rare. Presumably, as in January 1992, they are associated with a strongly disturbed polar vortex.

Finally, Pyle *et al.* (1995) have run some very high spatial resolution model studies (about 1° × 1° in the horizontal) for both the SESAME and ASHOE (Antarctic and Southern Hemisphere ozone expedition) campaigns. They found excellent agreement between models and data on a number of occasions when vortex air (characterized, for example, by elevated active chlorine concentrations) was found outside the vortex. Their study demonstrates conclusively that air is removed from the vortex edge and can contribute to the ozone decline found in middle latitudes.

3. Summary

Our understanding of polar ozone has advanced dramatically since the discovery of the ozone hole in 1985. The advances in modelling capability and in the quality of atmospheric data since then offer a tremendous opportunity for understanding the new problems which have emerged, including the question of the connection between polar processes and middle latitudes. It is clear that the Arctic vortex can become every bit as perturbed chemically as its Southern Hemisphere counterpart. Chemical depletion of ozone undoubtedly occurs in the north. During the cold stratospheric winter of 1994/95, SESAME scientists reported ozone decreases of up to 50% within the polar vortex between 12 and 20 km (press release issued by DGXII of the European Commission on behalf of SESAME scientists, 30 March 1995). This appears to be the largest loss seen so far in the north. As stratospheric chlorine levels decrease early next century, in response to international regulations, the ozone loss should decline.

Attention is now focused on middle latitudes. Observational studies show that air, primed for ozone depletion, can be stripped from the vortex edge into middle latitudes. Models are also being used in high spatial resolution integrations to study the mixing process. The filaments of air, torn from the vortex edge, have now also been modelled. Sometimes the filaments are thin, tube-like structures; on other occasions they appear to have a greater vertical extent. In either case they seem to provide a mechanism by which air, activated in polar regions, can be mixed into middle latitudes and contribute to the ozone loss there.

References

Chipperfield, M. P. 1994 A 3-D model comparison of PSC processing during the Arctic winters of 1991/92 and 1992/93. *Ann. Geophys.* **12**, 342–354.

Chipperfield, M. P., Cariolle, D. & Simon, P. 1994 A 3D transport model study of chlorine activation during EASOE. *Geophys. Res. Lett.* **21**, 1467–1470

Dahlberg, S. P. & Bowman, K. P. 1994 Climatology of large scale isentropic mixing in the Arctic winter stratosphere, *J. geophys. Res.* **99**, 20585–20599.

Fisher, M. A., O'Neill, A. & Sutton, R. 1993 Rapid descent of mesospheric air into the stratospheric polar vortex. *Geophys. Res. Lett.* **20**, 1267–1270.

MacKenzie, A. R., Knudsen, B., Jones, R. L. & Lutman, E. R. 1994 The spatial and temporal extent of chlorine activation by polar stratospheric clouds in the Northern Hemisphere winters of 1988/89 and 1991/92. *Geophys. Res. Lett.*, **21**, 1423–1426.

Norton, W. A. 1994 Breaking Rossby waves in a model stratosphere diagnosed by a vortex-following coordinate system and a technique for advecting material contours. *J. atmos. Sci.* **51**, 654–673.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Plumb, R. A., Waugh, D. W., Atkinson, R. J., Schoeberl, M. R., Lait, L. R., Newman, P. A., Browell, E. V., Simmons, A. J. & Loewenstein, M. 1994 Intrusions into the lower stratospheric Arctic vortex during the winter of 1991/92. *J. geophys. Res.* **99**, 1089–1106.

Pyle, J. A., Carver, G. D. & Schmidt, U. 1994 Some case studies of chlorine activation during the EASOE campaign. *Geophys. Res. Lett.* **21**, 1431–1434.

Pyle, J. A., Chipperfield, M. P., Kilbane-Dawe, I., Lee, A. M., Stimpfle, R. M., Kohn, D., Renger, W. & Waters, J. W. 1995 Early modelling results from the SESAME and ASHOE campaigns. *Faraday Discuss.* **100**. (In the press.)

Rood, R., Douglass, A. & Weaver, C. 1992 Tracer exchange between tropics and middle latitudes. *Geophys Res. Lett.* **19**, 805–808.

Waugh, D. W. 1993 Contour surgery simulation of a forced polar vortex. *J. atmos. Sci.* **50**, 714–730.

WMO 1995 Scientific assessment of ozone depletion: 1994. *WMO Ozone Res. Monitoring Proj. Rep.* No. 37.

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