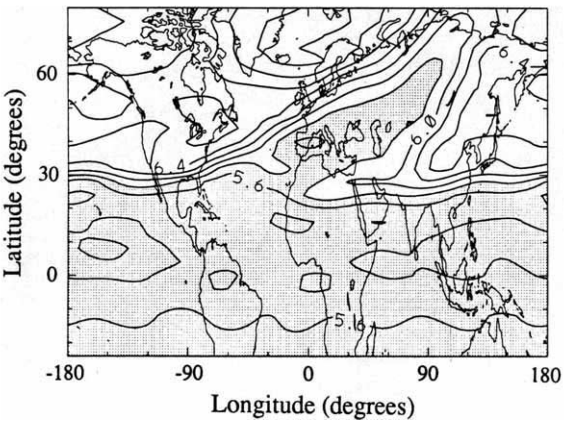

FIG. 4 Map of water vapour mixing ratio (p.p.m.v.) on the 1,100 K isentropic surface on 16 February 1993.

actions are emphasized in the constituent data (for example, the tropical N_2O values south east of Africa in Fig. 2*c*).

Figure 4 shows a diagram of a similar tongue - like structure in the distribution of water vapour for a wave event during Northern Hemisphere winter. A sequence of such maps (not shown) reveals separation of contours and the implied mixing of subtropical air into middle and high latitudes; note that the latitudinal excursions are larger for this case than for that in Figs. 2 and 3, as planetary wave amplitudes are typically larger in the Northern Hemisphere stratosphere. The evidence of wave transports out of low latitudes are most apparent in these constituent data during late winter–spring in both hemispheres; this time period is highlighted because the background tracer structure varies substantially with the seasonal circulation, with strongest subtropical gradients observed during late winter–spring.

The impression gained from the tracer measurements described here is that the subtropical transports appear mostly unidirectional—that is, material moves from the tropics to midlatitudes but not vice versa. This behaviour is similar to planetary-wave erosion of the polar winter vortices, where material is pulled off the outer edge and mixed into midlatitudes, but little transport into the vortex is found[17]. High-resolution simulations indicate that much of the erosion of the polar vortices occurs in the form of narrow filamentary structures, which cannot be observed in coarse-grain satellite data (but which are seen in aircraft observations)[20]. Similarly, it is possible that erosion of the subtropical barrier also occurs via filamentation, in addition to the large-scale planetary waves observed here. Further analyses of UARS constituent data will allow insight into transport mechanisms and couplings between high and low latitudes; numerical simulations[21] clearly show strong coupling between the low latitude perturbations shown here and planetary wave deformations of the polar vortex. □

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Subtropical stratospheric mixing linked to disturbances in the polar vortices

Darryn W. Waugh

Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

RANDEL *et al.*[1] have observed tongues of stratospheric air stretching from the tropics into middle latitudes, and conclude that such events may be responsible for transporting significant amounts of stratospheric air across the tropical–mid-latitude barrier[2]. Here I examine the movements of air parcels during these events using high-resolution contour-trajectory calculations. My calculations suggest that the tongues of tropical air are associated with disturbances of the stratospheric polar vortices. The edge of the disturbed polar vortex reaches low latitudes, and draws a long tongue of tropical air around the vortex into middle latitudes. This process occurs in the winter of both hemispheres, although the edge of the larger Antarctic polar vortex reaches farther toward the Equator, and draws up material from lower latitudes, than its Arctic counterpart.

Measurements from the recently launched Upper Atmosphere Research Satellite (UARS) are providing valuable insights into the distribution of trace constituents and fluid motions throughout the middle atmosphere. Randel *et al.*[1] have recently analysed global measurements of the long-lived stratospheric tracers nitrous oxide (N_2O) and water vapour (H_2O), which are measured by the Cryogenic Limb Array Etalon Sounder (CLAES) and the Microwave Limb Sounder (MLS) instruments on UARS, respectively. This analysis has shown that there are strong meridional gradients at low latitudes in the middle and upper stratosphere (altitude 28–42 km). The existence of these strong gradients confirms earlier suggestions[2] that there is a barrier to quasi-horizontal transport from the tropics into middle latitudes. But Randel *et al.*[1] also showed events where tongues of tropical air extend deep into middle latitudes. These tongues stretch and appear to break into isolated 'patches', suggesting that there is irreversible mixing and transport of tropical air into middle latitudes. This apparent subtropical wave breaking is analogous to wave breaking at the edge of the polar vortex[3–5]. Tongues of tropical air have also been detected in previous observational data[5], and in numerical models[7,17].

Here we examine the formation of these tongues of tropical air using 'contour advection with surgery' (CAS) calculations (this technique is described by Waugh and Plumb[6]; similar approaches have been used by Norton[7] and Schoeberl *et al.*[8]). In CAS calculations the evolution of material contours on a given isentropic surface is determined by advecting the contours by the daily, analysed balanced winds on that surface (as calculated from stratospheric analyses provided by the National Meteorological Center (NMC)). The resolution of the contours is maintained as they evolve, and very small-scale features are eliminated, using 'contour surgery' procedures[9]. Comparisons of CAS calculations with aircraft observations of chemical tracers[10,11] have shown that these calculations can accurately resolve fine-scale features (much smaller than those resolvable by operational satellites) in the stratospheric transport of tracers.

During 6–10 September 1992 a tongue of tropical, upper-stratospheric air was observed (in both the N_2O and H_2O data) to extend into southern middle latitudes (see Figs 2 and 3 in ref. 1). Fig. 1 shows the results from a CAS calculation on the 1,100 K isentropic surface (altitude 38 km) for this period. The material-contour calculation was started on 1 September at the 15° S latitude circle (this is in the region of strong gradients observed by UARS, see Fig. 1 of ref. 1). There is excellent agreement between the CAS calculation and the the observed tracer distributions (Figs 2 and 3 in ref. 1). A tongue of tropical air extends over South America into middle latitudes and this tongue then stretches out and forms a 'patch' of tropical air over the southern Indian Ocean. As in previous comparisons[10,11], the CAS calculation produces fine-scale filamentary features not detectable in the satellite data, for example the thin strands of tropical air joining the 'patch' over the southern Indian Ocean to lower latitudes. These strands narrow and lengthen with time, eventually reaching scales where diffusive processes mix the tropical and middle latitude air. The good agreement between the CAS calculations and the UARS data implies that the balanced winds derived from NMC analyses accurately describe the tropical flow field.

Randel *et al.*[1] noted that the intrusions of tropical air into middle latitudes can also be detected in maps of Ertel potential vorticity (PV) on the 1,100 K isentropic surface. Potential vorticity is a materially conserved quantity for adiabatic, frictionless flows, and provides a powerful diagnostic indicator of the fluid motions[12,13]. Maps of PV for 6–10 September 1992 also show strong deformations to southern high-latitude contours (for example Fig. 3 of ref. 1), which suggests that there is also transport from the edge of the polar vortex into middle latitudes. The high-latitude tracer transport, and interaction with low latitudes, is now examined using CAS calculations started with contours of PV (calculated from NMC analyses).

Figure 2 shows the evolution, from a CAS calculation, of two material contours: the dark-shaded inner contour was initially at the outer edge of the Antarctic polar vortex, whereas the light-shaded outer contour was initially at the southern edge of the region of strong gradients in the tropics. These maps are polar stereographic projections, with South America at the top of the map. The tongue of tropical air shown in Fig. 1 now appears as a thin (lightly-shaded) ribbon on the right side of the map, which by 10 September extends from the top to the bottom of the map. The time sequence of these plots suggests that this tongue of tropical air is produced by the movement of the polar vortex to lower latitudes. As the polar vortex moved off the pole, the outer edge reached low latitudes (for example, 30° S over South America on 6 September) and draws tropical air to higher latitudes. This tropical air formed a thin tongue which was stretched and wrapped around the vortex. The calculation also shows that during this period tongues of air from the outer edge of the polar vortex are mixed into middle latitudes. This transport of material, away from the edge of the vortex in long thin filamentary tongues, is characteristic of planetary-scale Rossby wave-breaking at the edge of the polar vortex in the middle and upper stratosphere[3-5]. The filamentary structures in middle latitudes can not be detected in satellite data, but have been detected in aircraft observations[10,11,14,15].

The tongue of tropical air has very deep vertical structure, and is present in the lower stratosphere (for example, 450 K isentropic surface, altitude 17 km). The tongue was not detected in the UARS data at the lower levels, presumably because the trace constituents do not have strong gradients at these levels[1]. But satellite measurements of aerosols (taken soon after the eruption of Mount Pinatubo) show a tongue of tropical, lower-stratospheric air penetrating into southern middle latitudes[16]. CAS calculations on the 500 K isentropic surface for this period show very similar evolution to that described above, again suggesting that the formation of the tropical tongue was associated with the movement of the edge of the polar vortex.

The evolution described above also occurs in the Northern Hemisphere winter. Figure 3 shows the position of two material contours on 16 February 1993 from a CAS calculation on the 1,100 K isentropic surface started on 10 February. The inner contour was initially at the outer edge of the Arctic vortex whereas the outer contour was at the northern edge of the strong gradients in the tropics. As in the Southern Hemisphere case,

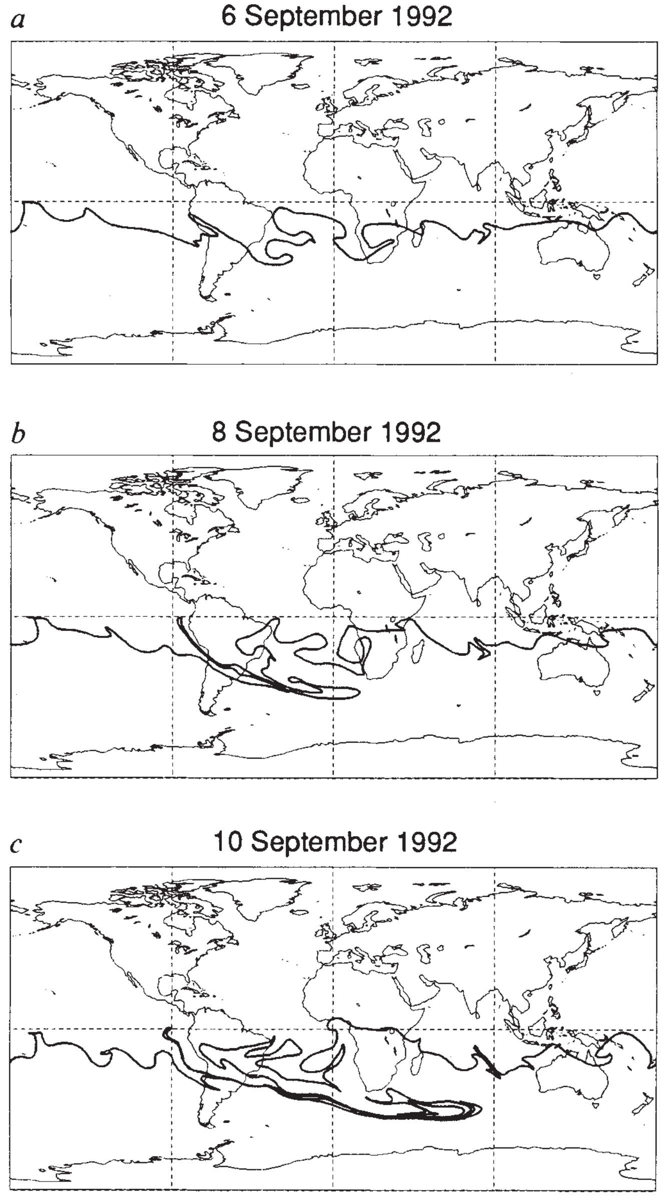

FIG. 1 *a*, *b*, *c*, Evolution of a material contour on the 1,100 K isentropic surface (approximate altitude 38 km and pressure 5 mb) for 6–10 September 1992, as determined by a CAS calculation. The calculation was started on 1 September 1992 at the 15° S latitude circle.

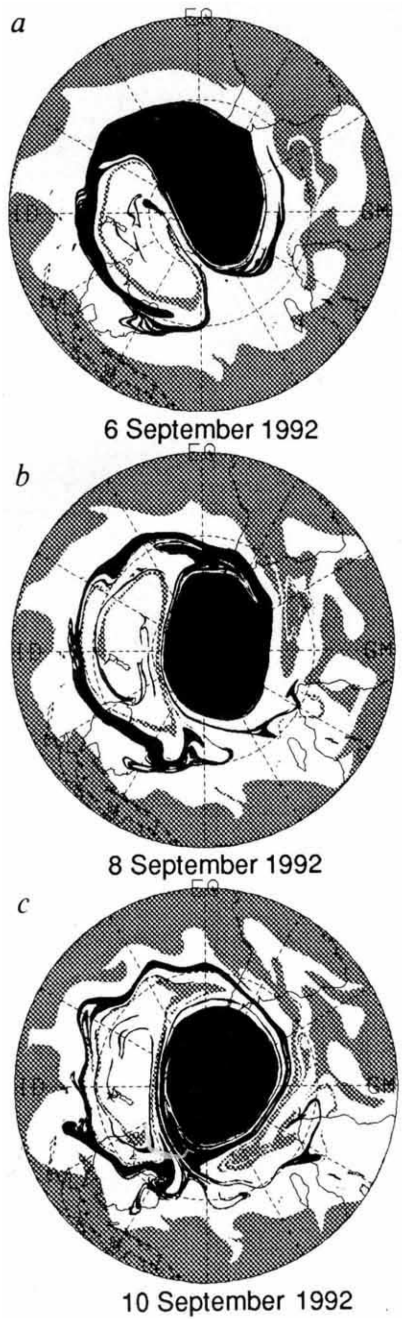

FIG. 2 *a*, *b*, *c*, Evolution of material contours at the edge of the polar vortex (dark-shaded region) and the strong gradients in the tropics (light shading) on the 1,100 K isentropic surface for 6–10 September 1992, as determined by a CAS calculation. The initial contours are at the analysed locations of the -7×10^{-4} and -3×10^{-4} K m^2 s^{-1} kg^{-1} contours of Ertel PV (see text) on the 1,100 K surface on 1 September 1992. Maps are polar stereographic projections with the Greenwich meridian to the right.

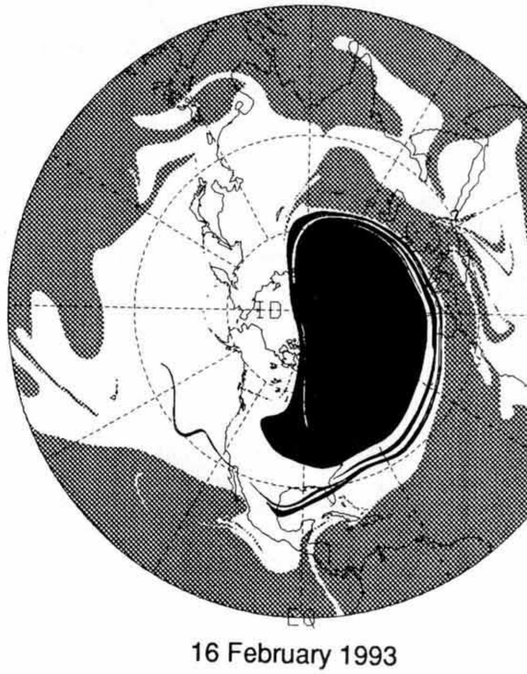

FIG. 3 Position of contours at the edge of the polar vortex (dark-shaded contour) and the strong gradients in the tropics (light shading) on the 1,100 K isentropic surface on 16 February 1993, as determined by a CAS calculation started on 10 February. The initial contours are at the analysed locations of the 8×10^{-4} and 4×10^{-4} K m^2 s^{-1} kg^{-1} contours of Ertel PV (see text). Map is a polar stereographic projection with the Greenwich meridian to the right.

the polar vortex is distorted into a comma-shape and is centred away from the pole. The time sequence of maps shows the edge of the vortex reaching low latitudes and drawing a tongue of tropical air over Europe and around the vortex. The structure and position of this tongue on 16 February agree well with the H_2O observations from UARS (see Fig. 4 of ref. 1). Again, there are also breaking Rossby waves at the edge of Arctic vortex, and thin tongues of both polar and tropical air are transported (and mixed) into middle latitudes.

Although the evolution during the above periods is similar, the edge of the larger, although less mobile, Antarctic polar vortex reaches further towards the Equator than its Arctic counterpart, and material from lower latitudes is mixed into southern middle latitudes. Hence the extent of movement of the edge of the polar vortex may explain the hemispheric difference between the observed position of the region of strong gradients in the tropics (the strong gradients of N_2O in the Northern Hemisphere winter are at 20–30° N compared with 5–15° S in the Southern Hemisphere winter[1]). □

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