Stratospheric transport from the tropics to middle latitudes by planetary-wave mixing

W. J. Randel*, J. C. Gille*, A. E. Roche†, J. B. Kumer†, J. L. Mergenthaler†, J. W. Waters‡, E. F. Fishbein‡ & W. A. Lahoz§

* National Center for Atmospheric Research, Boulder, Colorado 80307, USA
† Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304, USA
‡ Jet Propulsion Laboratory, Pasadena, California 91109, USA
§ Department of Meteorology, Edinburgh University, Edinburgh EH9 3JZ, UK

TRANSPORT of air from the troposphere to the stratosphere takes place mainly in the tropics[1]. By studying satellite records of the dispersal of volcanic aerosols from tropical eruptions, Trepte and Hitchman[2] concluded that there is a barrier inhibiting the transport of stratospheric air from the tropics to middle latitude, raising the question of how stratospheric material that has been transported from the troposphere is subsequently conveyed to higher latitudes. Here we present global maps of nitrous oxide and water mixing ratios obtained by the Upper Atmosphere Research Satellite. We see strong latitudinal gradients in these trace species, confirming the existence of a barrier to transport. But superimposed on this background structure we also see planetary-scale 'tongues' of tropical stratospheric air extending out into middle latitudes, and time sequences show irreversible mixing from the tropics into middle latitudes. Such episodes could be responsible for transporting significant quantities of stratospheric air across the tropical barrier.

Two long-lived stratospheric trace constituents are analysed here, namely nitrous oxide (N_2O) and water vapour (H_2O). Data on N_2O are obtained by the Cryogenic Limb Array Etalon Sounder (CLAES) on the Upper Atmosphere Research Satellite (UARS)[3], and data on H_2O are obtained from a separate instrument on UARS, the Microwave Limb Sounder (MLS)[4]. Identification of the wave structures in these independent data increases confidence in their reality, and provides a means of validating them. The satellite yaws at intervals of ~1 month, providing coverage from 30° latitude in one hemisphere to 80° in the other for successive periods. Orbiting-satellite data are mapped on standard pressure surfaces using a Kalman Filter technique[5], which results in daily maps of the constituent fields. The data are mapped with a ~4° latitude resolution, and a longitudinal truncation at zonal wavenumber 6 (~30° longitudinal resolution); the vertical resolution is ~2.5 km. Because of higher noise levels in the CLAES data, they are smoothed slightly in latitude and height before plotting.

The longitudinally averaged structure of the N_2O distribution during 1–20 September 1992 is shown in Fig. 1 (data north of 30° N were taken from the previous north-looking yaw interval). The source region for N_2O is near the Earth's surface. Nitrous oxide is well mixed in the troposphere (the lowest 15 km of the atmosphere), and decays with height in the stratosphere due to photochemical destruction above 40 km. The photochemical lifetime of N_2O below 40 km is >100 d (several years below 30 km), so that the distribution in the stratosphere is determined mainly by the circulation. As shown schematically in Fig. 1, rising motion in the tropics is associated with a maximum in N_2O over ~10° S to 30° N, and sinking motions over high latitudes of both hemispheres result in relatively low N_2O values. This downward displacement is particularly large over the South Pole at this time of year, so that the polar vortex is reflected in strong latitudinal N_2O gradients; rather more pronounced gradients across the Southern Hemisphere polar vortex are observed in UARS methane (CH_4) observations[6]. Horizontal transport by

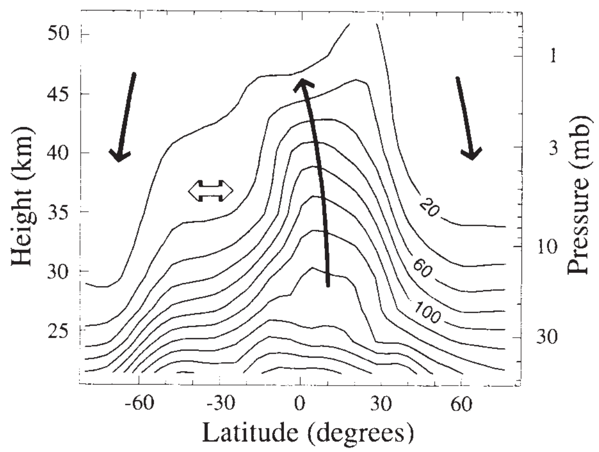

FIG. 1 Longitudinally averaged structure of nitrous oxide (N_2O) mixing ratio (in parts per billion (10^9) by volume (p.p.b.v.)) during 1–20 September 1992 measured by the CLAES instrument on UARS. Heavy solid lines denote the mean stratospheric circulation in the latitude–height plane, and the horizontal arrows denote the location of quasi-horizontal mixing by planetary waves.

planetary waves in the winter stratosphere results in a well mixed region between midlatitudes and subtropics, known as the 'surf zone'[7–9]; this is seen in Fig. 1 as the region of relatively flat N_2O gradients over 20–50° S. This overall structure of the N_2O distribution is in good agreement with previous satellite observations[10], and with idealized models of the mean stratospheric circulation that include the effects of planetary-wave transport[11].

Figure 2 shows a sequence of horizontal maps of the global N_2O distribution over 30° N–80° S on the 1,100 K isentropic surface (altitude ~38 km). Superimposed on the background structure of high values in the tropics is a tongue of high-N_2O air extending from the tropics deep into midlatitudes, with a distinctive NW–SE phase tilt. Similar tongue-like features have been found in satellite measurements of stratospheric ozone[9] and aerosol[22], and have also been noted in three-dimensional simulations of stratospheric tracers[12,13,23]. This characteristic tongue-like structure is observed from late August throughout the middle of September, when it remains fixed geographically but modulates in intensity. The time period in Fig. 2 is near the amplitude maximum, and perturbations associated with the tongue are discernible between the equator and 50° S. Similar wave patterns are observed at all vertical levels over ~28–42 km, which is the altitude range over which the strong subtropical N_2O gradients are found (Fig. 1). The time sequence of N_2O fields in Fig. 2 shows evolution of the tongue over a five-day period: stretching of the tongue into middle latitudes is followed by the breaking off of a patch of high-N_2O air near 40° S on September 10. This isolated patch of high-N_2O air retains its identity in middle latitudes until at least September 20, when the satellite yaws into a north-looking configuration.

Figure 3*a* shows a map of the 1,100 K water vapour distribution on September 8, obtained from MLS measurements. Water is also a long-lived tracer in the lower and middle stratosphere, with relatively low values in the tropics related to the upward tropical circulation (Fig. 1), and freeze-out near the cold tropical tropopause[14]; the mean structure is similar to that of N_2O, but with high and low values inverted. The water distribution in Fig. 3*a* shows a tongue-like structure very similar to that seen in the N_2O data, with relatively dry air extending from the tropics to midlatitudes. In a similar manner to the N_2O evolution seen in Fig. 2, this tongue of dry air is observed to stretch and break, with a net transport of dry air from the tropics to midlatitudes. Although the overall budgets of these tracers have not been

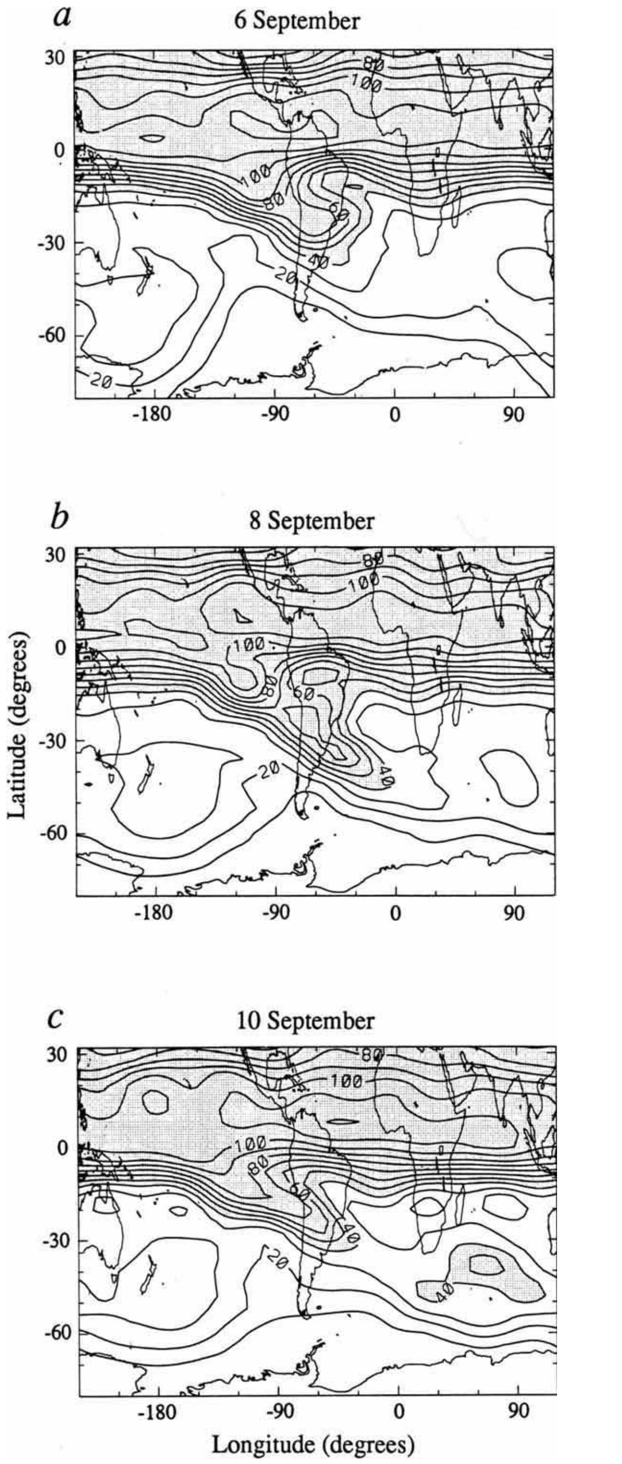

FIG. 2 *a–c*, Sequence of near-global maps of nitrous oxide (N_2O) mixing ratio (p.p.b.v.) on the 1,100 K isentropic surface for 6–10 September 1992. This isentropic level is near an altitude of 38 km, and close to a pressure surface of 5 hPa.

quantified, such transports out of the tropics are a possible factor contributing to the dehydrated midlatitude stratosphere observed over the Southern Hemisphere in October[15].

Figure 3*b* shows a map of potential vorticity (PV) on the 1,100 K isentrope for 8 September. Potential vorticity is a conservative quantity often used for diagnosis of atmospheric fluid dynamics, in particular for variations associated with planetary-wave transience and mixing[7–8,16–18]. Here PV is calculated by combining MLS temperature data with base-level geopotential heights from the US National Meteorological Center (NMC), and then deriving balanced winds and potential vorticity[19]; the PV data are truncated to the same resolution as that used for the constituent data. The PV patterns in Fig. 3*b* show strong gradients in high latitudes (identifying the polar vortex), and a secondary region of tightened contours near 10°–20° S (the subtropical PV barrier). The PV structure shows clearly a tongue of low- (tropical-) PV air extending into midlatitudes, and the similar patterns seen in three completely independent quantities (N_2O, H_2O and PV) are strong evidence for the reality of this feature. A sequence of PV maps (not shown) reveals that the drawing out of this subtropical tongue occurs subsequent to a planetary wave deformation of the polar vortex (note the asymmetry of the vortex in Fig. 3*b*); as the vortex is deformed towards low latitudes, the associated winds advect material out of the tropics into middle latitudes (this is shown clearly in numerical simulations of this event[21]). Material exchanges between high and low latitudes are evidenced in these data by the separation (breaking) of PV and tracer contours; this irreversible exchange due to large scale motions is what we refer to as planetary wave mixing. We note, however, that the overall material exchanges are viewed somewhat differently depending on the background gradients: the PV structure highlights exchanges between the polar vortex and midlatitudes (note the polar PV remnants west of South America in Fig. 3*b*), whereas tropical–midlatitude inter-

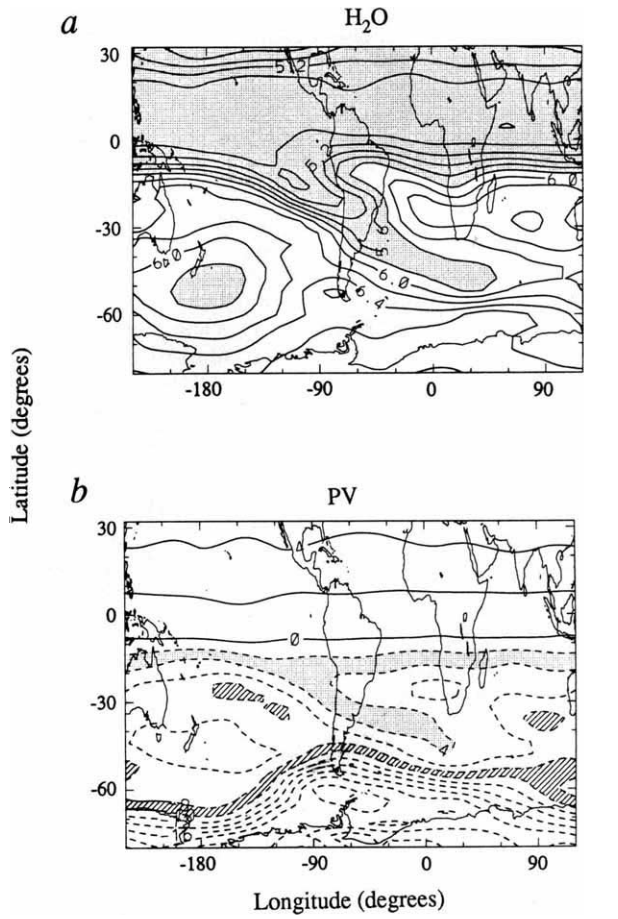

FIG. 3 Maps of water vapour mixing ratio (*a*, units of p.p.m.v.) and potential vorticity (*b*, units of 10^{-4} K m^2 kg^{-1} s^{-1}) on the 1,100 K isentropic surface on 8 September 1992. Water vapour data are from the MLS instrument on UARS, whereas potential vorticity is derived from MLS temperature and NMC base-level geopotential data (see text). Note the similarity in spatial structure between these data and the CLAES-derived nitrous oxide (Fig. 2*b*).

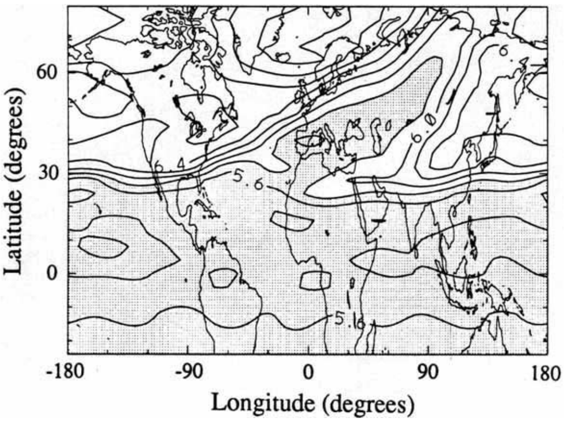

FIG. 4 Map of water vapour mixing ratio (p.p.m.v.) on the 1,100 K isentropic surface on 16 February 1993.

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