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# TRACER EXCHANGE BETWEEN TROPICS AND MIDDLE LATITUDES

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Abstract. The interaction between the tropics and middle latitudes is studied using a tracer emitted at 50 hPa along a great circle route between Los Angeles, USA and Sydney, Australia. Though designed to examine the impact of stratospheric aircraft, the study more generally addresses the transport between tropics and middle latitudes for a three month period from January through March 1989. The results show that air is transported from the tropics to middle latitudes by planetary scale and tropospheric cyclonic scale waves. Except for intrusions by these wave events, the tropics are substantially isolated throughout the lower stratosphere. These waves draw material out of the tropics which ends up in the middle latitude westerly jets, with little material entering the winter polar latitudes prior to the springtime transition. The summer southern hemisphere is characterized by tracer being drawn out in streamers that extend from north and west to south and east. The material in the tropics is zonally asymmetric. The material that reaches the troposphere comes down in the synoptic scale eddies and is concentrated in the middle latitude jet stream. These characteristics are similar to those observed during the dispersion of volcanic clouds.

## Introduction

Most tracer studies of the stratosphere using models have concentrated on planetary wave transport during winter, and recently much of the research has focussed on the interaction of the northern and southern polar vortices with the middle latitudes [e. g., Rood et al., 1992, Tuck et al., 1992, Schoeberl et al., 1992; Schoeberl and Hartmann, 1991]. Transport within the tropics and the interaction of the tropics with middle latitudes is not as completely understood. One reason is the difficulty of understanding transport in a dynamic regime where the Coriolis force is small and the geostrophic balance weakens. Furthermore, despite a rich variety of waves in the tropics, it is often assumed that two-dimensional (2D) chemical assessment models are appropriate in the tropics.

Tropical transport characteristics must be known in order to address a wide variety of problems. Within the context of three-dimensional (3D) models, many of the inadequacies in our 3D simulations can be linked to problems in the tropics and/or middle latitude/tropical interactions [Rood et al. 1989, 1991; Allen et al., 1991]. For problems such as the assessment of the impact of stratospheric aircraft, the transport and fate of tropical tracers must be carefully quantified, particularly since assessment calculations employ 2D models.

This paper reports on a northern hemisphere wintertime simulation of a tracer emitted at 50 hPa on a great circle path between Los Angeles (USA) and Sydney (AUS). The simulation is at the end of the westerly phase of the QBO, and provides a clean exposition of numerous transport features. These include the surprising degree of zonal asymmetry that develops in the tropics as well as the identification of preferential longitudes for tropical middle latitude exchange. The study will focus on the transient behavior of the tracer as it is transported from the tropical source region to extratropical latitudes. The focus on this transient phase helps to reveal transport mechanisms explicitly.

## The Model

The model has been described in several previous papers [Rood et al., 1991, 1992; Allen et al., 1991]. Winds are derived by the assimilation of atmospheric temperature and wind data with a conventional forecast assimilation system, STRATAN. Because of the use of assimilated data products, this simulation represents a particular time interval. These winds are used in a chemical transport model (CTM) to calculate the tracer advection. No explicit diffusion is added to the calculation, but there is nonlinear, scale dependent diffusion in the horizontal advection algorithm. The horizontal resolution of the CTM is 2° latitude by 2.5° longitude. The vertical domain is from the ground to 0.4 hPa. The vertical resolution is on the order of 2-3 km in the upper troposphere and lower stratosphere. The vertical transport calculation is diffusion free.

Previous publications about this model have focused on wintertime transport in the northern hemisphere. These studies have shown that transport associated with planetary and synoptic scale disturbances is well represented. This is the first study with this model that focuses on the tropical transport characteristics. For this experiment a conservative tracer has been emitted on the 53 hPa model level along a great circle route between Sydney (SYD) and Los Angeles (LAX). The emission is continuous in time and starts on 28 December 1988. Ostensibly, this represents the effluent of a hypothetical supersonic airplane flying in the lower stratosphere.

## Results

Figure 1 shows a contour diagram of the zonal wind averaged between 16 and 31 January 1989. The corridor between LAX and SYD, marked on the figure, generally lies in easterlies. In the southern part of the corridor (5° to 30° S) the easterlies are well defined and encircle the globe. In the

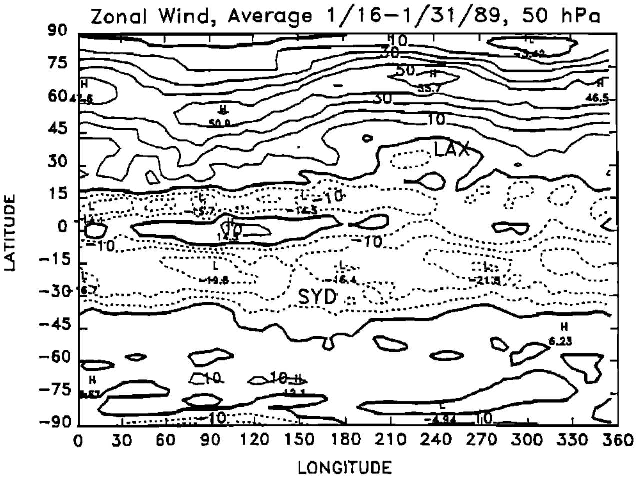

Fig. 1. The zonal wind at 50 hPa is averaged between 16 and 31 January 1989; the contour interval is 10 $ms^{-1}$ for positive winds (westerlies, solid), 5 $ms^{-1}$ for negative winds (easterlies, dashed). The zero contour is the bold solid.

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northern part of the corridor, the emissions are usually in easterlies, but the winds are not as zonally symmetric as in the southern hemisphere. Frequently between 10° and 30° N there are weak westerlies; however, over the Pacific west of LAX the tropical easterlies often protrude northward. Therefore, the northern part of the corridor flips between westerlies and easterlies.

Over Indonesia and the Indian Ocean (60° - 150° E) the winds are frequently westerly. Westerlies are sporadically present at the longitude of the corridor, and at all longitudes westerlies occasionally appear. More zonally symmetric westerlies are seen in the analyses from the European Center for Medium Range Forecasting (ECMWF) than in STRATAN. Both analyses show the westerlies that are present at the equator during the end of the westerly phase of the quasi-biennial oscillation (QBO).

Figure 2 shows a contour diagram of tracer, C, on the 53 hPa surface on 31 January 1989. The most remarkable feature is the extreme pollution of the corridor. At the latitudes of the persistent easterlies (5° - 30° S), a stream of tracer is removed from the corridor and moved around the globe. At these southern latitudes, as the corridor is approached from east to west there is a tremendous wall of tracer. At this time, the tracer has not been carried all the way around the globe, because northerly winds close to 300° E, most pronounced between 15° and 30° S, inhibit pure zonal transport. Between 180° and 300° E the time averaged meridional wind shows a series of steady synoptic scale features which transport tracer out of the easterlies on time scales that are shorter than the zonal advective time scale. The effect of synoptic scale disturbances can be seen by the dashed contours throughout the southern hemisphere where tracer is extracted from the tropics and stretched in a north and west to a south and east pattern. This pattern is the same as that associated with cloud bands [Salby et al., 1991]. Except for these areas of middle latitude cyclonic scale activity, there is substantial isolation of the tropics from middle latitudes.

At the most northern extreme of the tropics, the tracer is carried westward around the globe. However, because the easterlies in the northern tropics show more space and time variance than in the southern tropics, the tracer does not spread to all longitudes. Furthermore, between 30° and 150° E the middle latitude westerlies often protrude into the subtropics, and the associated meridional flow is northward. Therefore, tracer is removed northward out of the tropics and subtropics and advected eastward towards LAX. Some tracer gets caught in the periphery of the Aleutian anticyclone centered over the Pacific Ocean, and there is occasional transport into the core of anticyclone.

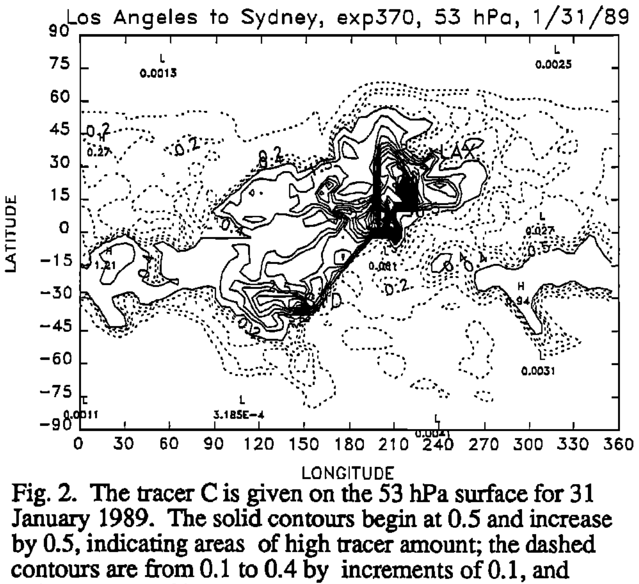

Fig. 2. The tracer C is given on the 53 hPa surface for 31 January 1989. The solid contours begin at 0.5 and increase by 0.5, indicating areas of high tracer amount; the dashed contours are from 0.1 to 0.4 by increments of 0.1, and indicate areas of low tracer amount.

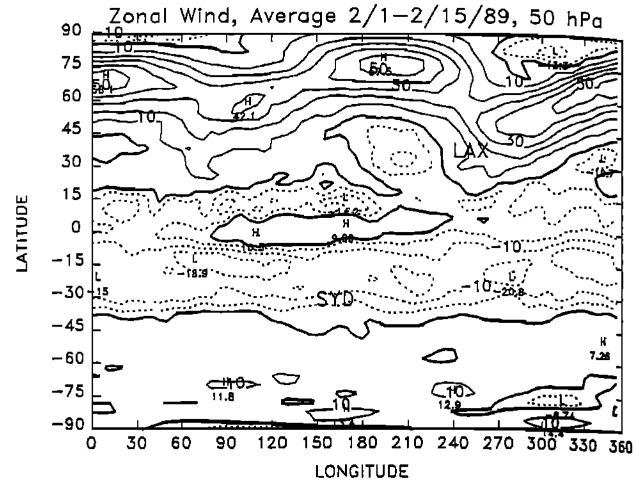

Fig. 3. The zonal wind at 50 hPa averaged between 1 and 15 February 1989; contour interval is the same as in Figure 1.

Between longitudes 60° and 120°E the westerlies at the equator, noted above, are more persistent than at other longitudes, and a large region over the Indian Ocean is less polluted. With the continuous emission, and the generally weak winds, material is not effectively evacuated from the corridor. Clearly, if the emissions into the tropics are zonally asymmetric, highly asymmetric distributions can persist for long periods of time. This is particularly true during the westerly phase of the QBO when the tropical winds are a mixture of easterly and westerly winds.

Figure 3 shows the time averaged zonal winds for the first 15 days of February. In the tropics the wind is similar to the earlier period. However, in northern middle latitudes there has been a significant change. The strong westerly middle latitude jet is more zonally asymmetric, driven largely by a strong wave number two stratospheric warming [Newman et al. 1990, Fairlie et al., 1990]. The northern end of the corridor is now in westerlies. Middle latitude cyclonic systems in the troposphere are guided by the middle latitude westerlies. Therefore, the stratospheric extension of weather systems become important mechanisms of transport out of the tropics.

Figure 4, from 15 February, shows the transport of C northward and eastward due to the westerly flow over LAX.

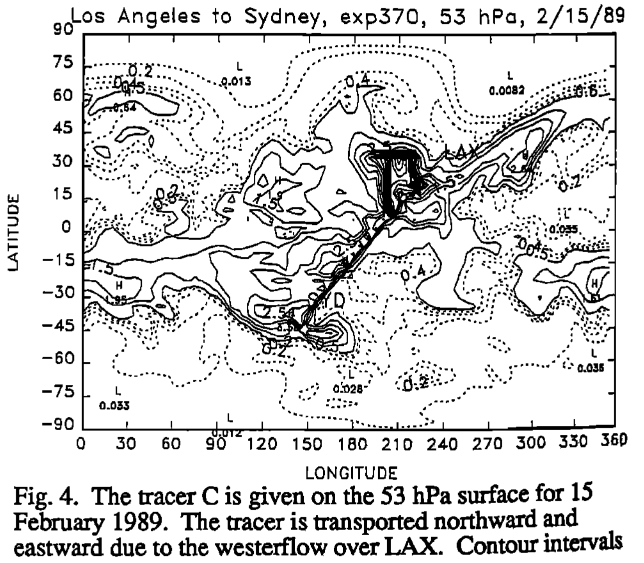

Fig. 4. The tracer C is given on the 53 hPa surface for 15 February 1989. The tracer is transported northward and eastward due to the westerflow over LAX. Contour intervals are as in Figure 2.

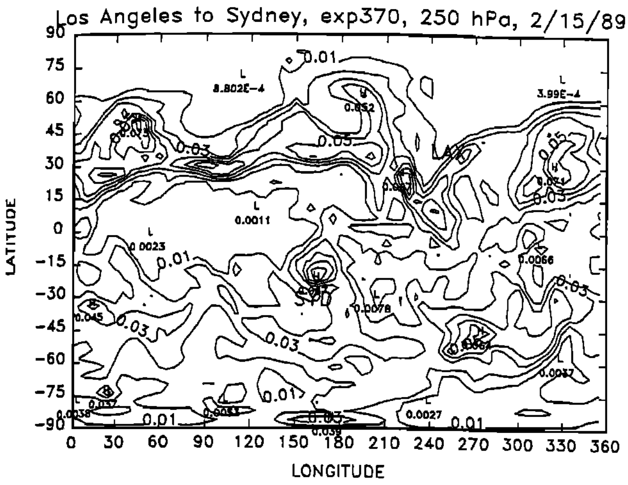

Fig. 5. The tracer C is given on the 250 hPa surface for 15 February 1989. The signature of the corridor is not visible, rather tracer maxima in both hemispheres are associated with storm systems. The contour interval starts at 0.01 and increases by 0.01.

Tracer is pulled into the middle latitude westerly jet and rapidly spread eastward in the core of the jet. There is very little transport to polar latitudes. Otherwise, many of the characteristics of the tracer distribution are the same as on 31 January, with a high degree of asymmetry in the tropics.

The tracer distribution at lower altitudes provides information on areas where stratosphere-troposphere exchange might be occurring, as well as a better picture of the role of the tropospheric weather systems. The 250 hPa distribution is given in Figure 5. In the tropics the 250 hPa surface is in the troposphere, but at polar latitudes it is in the stratosphere. The first things to note are the much decreased mixing ratios of the tracer and that the signature of the corridor is not visible. The middle latitude cyclones have picked up the pollutant and deposited it in the middle latitude storm belts. Centers of tracer maxima are present in the both hemispheres, showing that the tracer has become linked with storm systems. In the northern hemisphere the pole remains clean because the stratospheric vortex extends down to this altitude, and there is little transport into the vortex.

Figures 1-5 show that transport out of the tropics occurs in specific longitude bands and is often associated with episodic cyclonic scale disturbances. Once the material gets out of the tropics, it is not homogeneously mixed throughout the two hemispheres. In the northern hemisphere, if the material is injected into the westerly jet then it remains there taking on the structure of the predominant zonal wave 1 jet. There is some pollution seen in the Aleutian anticyclone. There is very little polluted air entering either the northern winter or southern summer polar vortex.

In the middle of March the northern hemisphere winter vortex has broken up and high latitude easterlies are forming. At the south pole the westerlies seen in Figures 1 and 3 are becoming more regular as the austral autumn begins. The contour plot of C (Figure 6) shows that the highly polluted corridor persists, with large zonal asymmetry in the tropics. In the easterlies between 15° and 20° S the tracer has finally encircled the globe, but a wall still persists as the corridor is traversed. The regimes of westerlies at the equator and in the northern subtropics remain largely unpolluted.

The extratropics are now quite different in the two hemispheres. In the northern hemisphere there is a large clean area centered at 60° N between 90° and 180° E. There is a much smaller clean area between 300° and 320° E at the same latitude. These clean areas are remnants of the wintertime polar vortex. Otherwise there is pollutant spread throughout the northern hemisphere. High values continue to be drawn out of the corridor at the northern end. The southern hemisphere is cleaner than the northern hemisphere, and the boundary between tropical and extratropical air becomes more distinct as the winter vortex starts to develop.

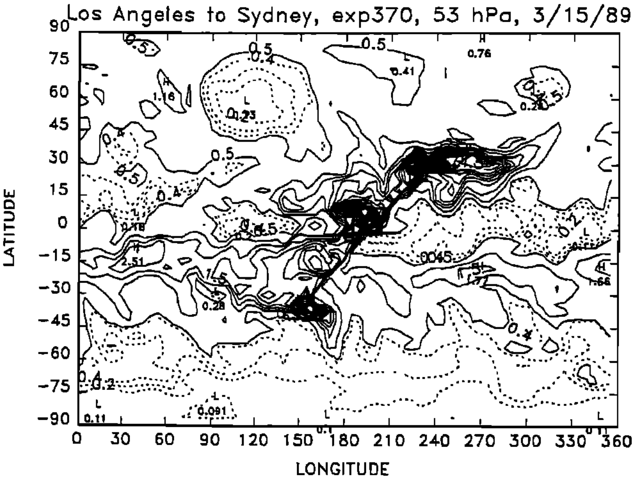

Fig. 6. The tracer C is given on the 53 hPa surface for 15 March 1989. The highly polluted corridor persists, with large zonal asymmetry in the tropics. Contour intervals are as in Figure 2.

The large zonal asymmetries in the tropics are due to the weak winds and the persistent westerlies at the equatorial and northern subtropical latitudes. Even with assimilation procedures, it is difficult to derive winds in the tropics. There are virtually no sonde data over the oceans, and much of the land surface is also devoid of wind data. Therefore, the state of the atmosphere is primarily defined by the temperature data and is strongly influenced by how the general circulation model and the analysis routines interpret the temperature data.

Given the more persistent equatorial westerlies noted above in the ECMWF analyses, the tracer experiments have been repeated with the ECMWF winds. This experiment primarily tests the sensitivity of the transport results to the westerlies over the equator, and the results of the two experiments are strikingly similar. Strong zonal asymmetry is modeled in the tropics, where both simulations show three areas of high pollution in the corridor (see Figure 6). At LAX and SYD the intrusions into the extratropics have similar geometries.

## Discussion and Conclusions

These studies show strong zonal asymmetries of aircraft effluent in the tropics during the westerly phase of the QBO. The pollution source is limited to the Pacific corridor, where much of the traffic is anticipated to occur. The zonal asymmetries arise because of the spatial distribution of the different regimes of easterly and westerly winds in the tropics.

The strong zonal asymmetries raise serious questions about the utility of 2D models in the tropics. The concentration of material in the corridor is more than a order of magnitude larger than the zonal mean. Given the relatively long advective time scales in the tropics, the continuous emission of aircraft exhaust in defined corridors, and time scales of stratosphere-troposphere exchange on the order of 1-2 years [Holton, 1990; Follows, 1992], it is not expected that the tropics will evolve to a zonally symmetric steady state.

Transport out of the tropics is influenced by planetary scale activity in the winter hemisphere and tropospheric synoptic scales in both the summer and winter hemispheres. The relationship to eddy activity assures that the transport out of the tropics is both episodic and a function of longitude, and are the same mechanisms found to erode the polar vortex [Rood et al., 1992]. As at middle and high latitudes, the tropospheric disturbances would be expected to become less important transport vehicles as altitude is increased. This is indeed observed in the model, and by 30 hPa there is apparently a strong transport barrier between tropics and middle latitudes. This barrier is most effectively violated by large amplitude planetary waves in the winter hemisphere.

The transport modeled here is consistent with the picture defined by the SAGE II observations (M. P. McCormick, personal communication). The SAGE data show substantial isolation between the tropics and middle latitudes with leakage occurring in episodic events of both planetary and synoptic scale. Veiga et al. [1991] show a dramatic example of extratropical transport into southern hemisphere middle latitudes, with the stretching of the material from north and west to south and east. Both the geometry and the spatial scale of this transport event is consistent with the model results.

Trepte and Hitchman [1992] have discussed the SAGE aerosol data as a function of phase of the QBO. During the easterly phase they find the aerosols are lofted to higher altitudes and confined to the tropics. During the westerly phase they find the aerosols more directed to lower altitudes, with an apparent increase of aerosol transport to the extratropics in the lower stratosphere and upper troposphere. These results are consistent with the transport mechanisms discussed in this study. Taken together, the two studies suggest that there will be years when the zonal asymmetry of tracers in the tropics is particularly high.

This study has not focused on stratosphere-troposphere exchange. Within the confines of the global model we do not expect the mechanisms of stratosphere-troposphere exchange to be represented accurately. However, the regions in which exchange takes place might be delineated. Figure 5 shows that when the tracer is emitted in the tropics, the bulk of the material that gets to lower altitudes is in the middle latitude storm bands. Given the annual cycle of the storm bands [James, 1983], transport into the northern hemispheric troposphere would be expected to occur more vigorously in winter than in summer. There is less annual variability in the position of the southern hemisphere middle latitude cyclones, but the cyclones are more vigorous in the winter. Therefore, annual variability is expected in the southern hemisphere, but with less amplitude than in the northern hemisphere.

Boville et al. [1992] have performed a Mount Pinatubo dispersion experiment with a conventional general circulation model (GCM). Their model shows substantial isolation of the tropics from the middle latitudes, with dispersion of the aerosol northward as the northern hemisphere winter begins. There is a region of preferred poleward and downward transport in the upper troposphere and lower stratosphere. The zonal mean representation of Boville et al. agrees with many of the characteristics observed by the SAGE instrument. However, even the best GCM's have biases between their simulations of large scale transport features and observations, and no GCM has properly represented the (QBO).

The assimilation transport approach has the advantage that the temporal and spatial structure of the planetary and synoptic scale waves are accurately represented. In the tropics, however, major shortcomings still exist with the wind estimates. This is indicated by the fact that tropical winds are a sensitive function of analysis techniques. Because there are virtually no direct wind data, the assimilation procedure depends on the model simulation as well as the interaction between the general circulation model and the objective analysis routines. It is reasonable to anticipate major improvements in tropical transport simulations over the next few years. This is due to improved modeling and analysis techniques, as well as the possible impact of direct wind measurements from the Upper Atmosphere Research Satellite (UARS). These improved simulations will allow much more confident assessments of stratospheric pollution from aircraft emissions.

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