Tropical Troposphere-to-Stratosphere Transport: A Lagrangian Perspective

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Introduction

A growing body of observations and theoretical considerations suggests that the transition from the troposphere to the stratosphere is gradual, rather than a relatively sharp discontinuity at the tropopause. In the tropics, it has been suggested that a tropical tropopause layer (TTL) spans the transition region from the convectively dominated overturning circulation of the Hadley cell to the region of slow upwelling (primarily wave-driven) of the lower stratospheric Brewer-Dobson circulation. Also see the article by Ian Folkins in this issue.

The transport of chemical tracers through the TTL is an important part of the global climate system. Air enters the stratospheric 'overworld' primarily in the tropics (Holton *et al.*,1995), and therefore processes in the TTL play a significant role in determining timescales for transport into the stratosphere of chemical species with tropospheric sources. For various reasons, among them the problem that current global-scale models cannot resolve individual convective cells penetrating the TTL, the modelling of chemical tracer transport in this region provides a formidable challenge. We have recently carried out a number of experiments with trajectory calculations based on 3-dimensional wind fields from global-scale atmospheric models and meteorological analysis datasets in order to characterize the circulation in the TTL as represented in these models and datasets. In particular, we focused on identifying typical pathways of tropical troposphere-to-stratosphere transport (TST), and their implications for stratospheric water vapour concentrations.

Here, we provide an overview of some of the results reported by Hatsushika and Yamazaki (2003) (henceforth HY03), Bonazzola and Haynes (2004) (henceforth BH04), Fueglistaler *et al.* (2004, 2005) (henceforth FWP04, FBHP05) and Fueglistaler and Haynes (2005) (henceforth FH05). HY03 used an atmospheric general circulation model with a resolution of T42L50, while the other experiments used data from the European Center for Medium-range Weather Forecasts (ECMWF). BH04 and FWP04 used operational analyses with resolutions of T106/L31 and T106/L50, and T511L60, respectively, and FBHP05 and FH05 used the ERA-40 reanalysis data with resolution T159/L60.

Circulation in the TTL and tropical TST

An intriguing result found in all experiments is that TST-trajectories enter the TTL predominantly over the western Pacific. This reflects the models' enhanced vertical transport due to convection over the western Pacific warm pool, and may have important implications, particularly for the transport of short-lived species into the stratosphere. We note, however, that this result needs careful interpretation given that none of the models explicitly resolves individual convective cells. An integration of these results from a global perspective with results obtained from mesoscale cloud resolving simulations is therefore an important and challenging task. It remains to be seen whether the latter lead to substantial changes of the picture obtained from the global-scale models.

Within the TTL itself, horizontal advection by the upper-level monsoonal anticyclones and the equatorial easterlies plays an important role in determining the path of TST trajectories. A small fraction of TST trajectories could be identified as travelling with the northern subtropical jet around the globe (the southern subtropical jet appears to be more detached from the circulation governing TST). Typically, TST trajectories were found to travel several thousand kilometers horizontally from their point of entry into the TTL to the point where they encountered their minimum temperatures. Experiments to determine average residence times in the TTL show a peak of about 13 days for a change of 10 K in potential temperature at 360 K, which is approximately the level of zero net radiative heating derived from radiative transfer calculations (Gettelman *et al.*, 2004).

The results of BH04 and FWP04 indicate that during boreal summer the distance travelled by the particles is shorter than during boreal winter, but that their ascent rate is faster during boreal winter, as expected from the annual cycle of the strength of the stratospheric Brewer-Dobson circulation. These results support the notion of Holton and Gettelman (2001) that horizontal advection is a crucial aspect of tropical TST. Our results, however, also emphasize the role of zonal inhomogeneities of vertical transport. Firstly, the convection over the western Pacific warm pool is the predominant source for air in the TTL, and eventually the stratosphere. Secondly, within the TTL this region is characterized by enhanced upwelling and an associated cold temperature anomaly. Matsuno (1966) and Gill (1980) showed that these planetary-scale features can be understood as a stationary, planetary-scale wave response due to localized heating in the troposphere as a result of convection over the western Pacific warm pool.

Figure 1 (see colour insert I) provides a schematic of tropical TST, emphasizing the role of the Western Pacific warm pool region and the upper-level anticyclones. During boreal summer, the Indian/Southeast-Asian monsoon is found to play a similar role, although it is much less symmetric around the equator as the convection, which plays an important role in determining the flux into the TTL and the pattern of horizontal circulation within the TTL itself, is shifted significantly to the north of the equator.

Experiments addressing interannual variability show that the largest modifications of the circulation patterns of tropical TST occur due to El-Nino/Southern Oscillation (ENSO) events. In particular, during El-Nino, convection is more homogeneous over the entire tropical Pacific, which in turn induces a homogenization of temperatures and circulation within the TTL.

Figure 2 (see colour insert II) shows the horizontal wind and temperature fields at 90 hPa from ERA-40 data during boreal winter for a strong La-Nina, a strong El-Nino situation, and the climatological mean state for the period 1979-2001. In addition, the figure shows the spatial density distribution where trajectories rising from the troposphere to the stratosphere are found to enter the TTL (red contour lines).

Stratospheric water vapour

Although it has been widely accepted since the seminal work of Brewer (1949) that the extremely low temperatures at the tropical tropopause constrain the water vapour flux into the stratosphere to a few parts per million by volume (ppmv), the details of the dehydration processes of tropical TST remain controversial. We therefore pursue two goals with the trajectory calculations. Firstly, we want to quantify the relevance of the previously discussed large-scale spatial structure of temperature and circulation in the TTL for water vapour mixing ratio of air entering the stratosphere (H_2O). Secondly, we want to quantify the degree to which observations of stratospheric water vapour concentrations can be explained by model calculations that greatly simplify cloud microphysics and mesoscale processes, but take into account the 3-dimensional temperature history of tropical TST as resolved by global scale models. Of particular interest in this context is the minimum temperature experienced by an air parcel as it ascends from the troposphere to the stratosphere. FBHP05 termed this point the 'Lagrangian cold point', to be contrasted with the traditional cold point tropopause.

In all experiments we found that the previously discussed circulation in the TTL is such that tropical TST trajectories efficiently sample the regions of lowest temperatures. Correspondingly, the spatial density distribution of the Lagrangian cold points as shown in Figure 2 (black contour lines) is highest in regions of lowest temperatures. These zonal temperature anomalies substantially lower H_2O compared to what might be expected from zonal mean tropical tropopause temperatures. Therefore we conclude that the large-scale 4-dimensional structure of temperatures and circulation in the TTL is crucial for understanding H_2O. FBHP05 showed that predictions of H_2O based on the saturation mixing ratio at the Lagrangian cold point of TST-trajectories agree very well with a broad range of observations, with a remaining moist bias of about 0.2 ppmv, or about 5% of H_2O.

Figure 3 reproduces some results shown by FBHP05 for mean entry mixing ratios of H_2O over selected periods, and the climatological mean annual cycle for the period 1992-2002. Note, for example, that the annual cycle of the model calculations based on the 3-dimensional temperature history of TST (Figure 3, cyan line) significantly improves the agreement with observations (Figure 3, black line) compared with a prediction based on tropical zonal mean cold point temperatures (Figure 3b, grey line). Remaining differences are discussed in detail by FBHP05, note for example that the obvious phase shift of approximately 1 month between the model prediction (cyan) and observation (black) is likely due to known problems of the stratospheric circulation in ERA-40 data.

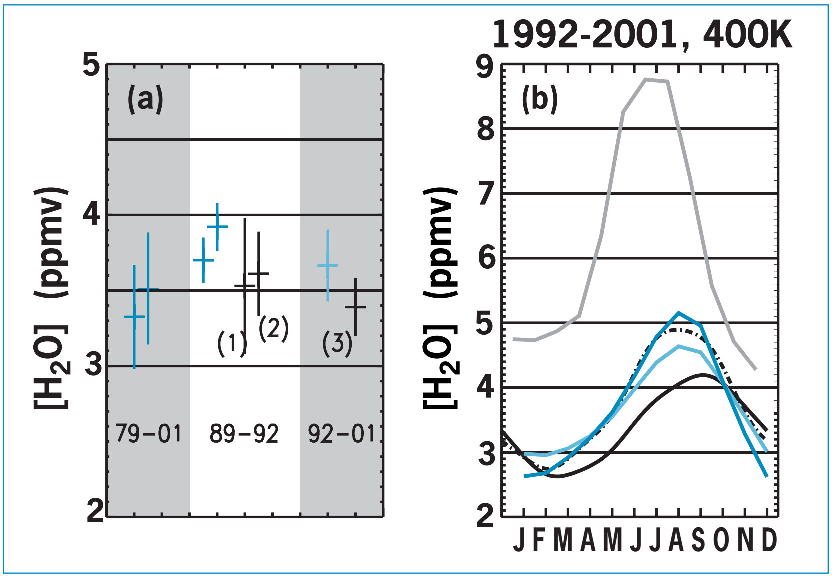

Figure 3: Comparison of model predictions and observations of stratospheric water vapour, taken from FBHP05. (a): Model predictions for concentration of water vapour $[H_2O]_e$ (blue, with (left) and without (right) taking into account the seasonal cycle of the strength of the stratospheric Brewer-Dobson circulation) and tropical (30°S-30°N) mean water vapour mixing ratio at 400 K potential temperature (cyan) for the periods 1979-2001, 1989-1992 and 1992-2001. Observations (black) of $[H_2O]_e$ are from Michelsen et al. (2000) (1) and Engel et al. (1996) (2), and (3) is the tropical mean water vapour mixing ratio at 400 K from HALOE. (b): Climatological mean annual cycle of model prediction for $[H_2O]_e$ (blue) and tropical mean at 400 K (cyan), HALOE at 380 K (black, dash-dot) and at 400 K (black, solid), and, for reference, the saturation mixing ratio of zonal mean (10°S-10°N) cold point tropopause temperatures based on ERA-40 data.

FH05 further showed that for the period 1995-2002 their model predictions can explain observed interannual variability of water vapour concentrations in the tropical lower stratosphere to within measurement uncertainties. Largest modulations of H_2O are found to result from the temperature perturbation around the tropical tropopause due to the Quasi-Biennial Oscillation (QBO) and due to strong El-Nino situations. Based on simulations of idealized ENSO situations, HY03 predicted that La-Nina situations should be drier than El-Nino. This was partly confirmed by FH05 in their reconstruction of H_2O for the period 1979-2001. However, the interference of ENSO with other processes that affect tropical tropopause temperatures, most notably the QBO, makes it difficult to classify unambiguously the effect of ENSO, particularly La-Nina situations, on H_2O.

Summary

The good agreement of model predictions with observations of stratospheric water vapour suggests that the trajectory calculations, and the assumption of dehydration to the saturation mixing ratio of the Lagrangian cold point, capture the main processes controlling H_2O. Thus, the synoptic-scale temperature history of tropical TST apparently can explain H_2O very well, and smaller scale effects such as overshooting convection apparently need not be invoked at first order. Consequently, it appears that current global-scale models may do a better job in representing tropical TST than might have been expected. That notwithstanding, a comprehensive theory explaining the spatio-temporal circulation and temperature structure of the TTL that encompasses all scales, from individual convective cells to the planetary-scale stationary wave pattern, and the role of the stratospheric Brewer-Dobson circulation, remains an important and ambitious task.

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