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# Tropical convective transport and the Walker circulation

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## Abstract

We introduce a methodology to visualise rapid vertical and zonal tropical transport pathways. Using prescribed sea-surface temperatures in four monthly model integrations for 2005, preferred transport routes from the troposphere to the stratosphere are found in the model over the Maritime Continent (MC) in November and February, i.e., boreal winter. In these months, the ascending branch of the Walker Circulation over the MC is formed in conjunction with strong deep convection, allowing fast transport into the stratosphere. At the same time, the downwelling branch of the Walker Circulation is enhanced over the East Pacific, compared to other months in 2005, reducing locally the upward transport from emissions below. We conclude that the Walker circulation plays an important role in the seasonality of fast tropical transport from the troposphere to the stratosphere and so impacts at the same time the potential supply of surface emissions.

## 1 Introduction

Identifying transport pathways of very short-lived halocarbons to the upper troposphere/lower stratosphere (UTLS) region is important for assessing stratospheric ozone depletion (Levine et al., 2007; Salawitch et al., 2005; Sturges et al., 2000). Especially important in this context are brominated organic compounds (e.g. bromoform), which can be readily oxidised to form highly ozone-depleting inorganic bromine compounds ($Br_y$), see for example Hossaini et al. (2010). These compounds are thought to play a role in determining stratospheric ozone concentrations and influencing the distribution of UTLS ozone, thereby affecting radiative heating and possibly regional-scale tropopause temperatures. Understanding regional changes in ozone, tropopause temperatures and stratospheric water vapour is crucial for future climate prediction, as shown for example in the context of the Asian summer monsoon (Braesicke et al., 2011) or the Tropical Tropopause Layer (TTL), see below.





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Tropical convection can provide an efficient transport pathway from the boundary layer to the TTL (Fueglistaler et al., 2009), a distinct layer below the tropopause. Differences in the strength and vertical extent of tropical convection are important for the efficiency of convective transport into the UTLS (Aschmann et al., 2011). One important circulation pattern in this context is the Walker circulation. The Walker circulation is a meridional circulation in which air at the surface flows from high pressure over the Eastern Pacific (EP) to low pressure over the Maritime continent (MC). Air rises over the MC (in conjunction with strong convection) and flows towards the EP region in the upper troposphere. Biogenic sources of $Br_y$ precursors (such as bromoform and dibromomethane) vary regionally in the Tropics (Quack and Wallace, 2003) and consequently the spatial distribution of deep convection in conjunction with availability of precursor emissions will determine the resulting $Br_y$ amounts above the rising branch of the Walker circulation.

Here, we focus on a case study of convective transport using a global forecast model with idealised tracers to answer the questions: what are the preferred tropical pathways for surface to upper troposphere/lower stratosphere transport? How do the pathways, and their tracer transport efficiencies, differ over the seasons?

## 2 Methodology

We use the UK Met Office Unified Model version 6.1 in a global forecast setup (Petch et al., 2007). The model version has 38 vertical levels with a model top at ~ 40 km and a horizontal resolution of ~ $0.8^{\circ} \times 0.5^{\circ}$ (corresponding to a grid spacing of ~ 60 km). Four model runs of 30 days each are performed using initial conditions from the UK Met Office's assimilated data for February, May, August and November 2005, as discussed in Hosking et al. (2010). They find that modelled temporal and spatial distribution of low OLR, which is one indicator of tropical convection, correlates well with satellite observations. We therefore assume that the model captures aspects of convective transport for this non-ENSO year well. In their model study, deep convective elevators rapidly lift air from 4–5 km up to 12–14 km, and the influx of tropospheric air entering the TTL (11–12 km) is similar for all tropical regions, with most convection stopping below ~ 14 km. Here, we assess the transport of 8 idealised tracers emitted at the surface in a latitude band of 20° N–20° S around the equator from the 8 tropical domains illustrated in Fig. 1. Each of the domains is 45° wide and is identified by a two letter acronym: Africa (Af), Indian Ocean (IO), etc. Each tracer is constantly emitted from the surface with a horizontally homogeneous flux of $1.0 \cdot 10^{-9}$ kg m$^{-2}$ s$^{-1}$ and has an infinite atmospheric lifetime thereafter. Vertical distributions of the eight tracers are analysed using the time mean mass mixing ratios from the last 10 days of each 30-day model integration.

Figure 2 shows an example of the mass mixing ratio of a tracer (shaded) emitted in the MC region in a longitude-height cross-section averaged over the tropical belt (20° N–20° S) and averaged over the last 10 days of a monthly integration (started at 00:00 UT, 1 November 2005). The model converts the prescribed emissions into concentrations and the winds advect the concentrations horizontally and vertically. The emphasis will be on the vertical transport with some consideration regarding the horizontal transport within the TTL. We have chosen three model surfaces to monitor vertical transport, as expressed by increases in tracer concentrations during the integration period. The first surface is near the bottom of the TTL at around 12.5 km, the next surface is in the middle of the TTL at around 14.6 km and the top surface is around 16.9 km, which is effectively the model's (tropical) cold point tropopause (CPT). The lower levels coincide closely with the lapse rate minimum (LRM, 12.5 km), and the level of clear-sky net-zero radiative heating ($Q_{clear} = 0$, 14.6 km), see also Hosking et al. (2010) for more details. In the example shown in Fig. 2, high relative tracer concentrations are found in the lower TTL, and coherently high mixing ratios are modelled at all altitudes below 15 km over the MC region, indicating efficient vertical transport. Consequently, high concentrations (~ 30 %) are modelled over the MC region at 12.5 km (solid green line) and 14.6 km (solid red line), with lower concentrations (~ 5 %) at 16.9 km (solid blue line). We introduce the following notation: $MC_{surf} \rightarrow MC_{12.5\,km}$, etc., to indicate a local



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vertical transport pathway between the surface and the LRM level (12.5 km) in the Maritime Continent region.

Figure 2 also indicates horizontal eastward tracer advection within the TTL from the MC region to the WP, CP and EP regions; such transport pathways are a combination of vertical and horizontal motion. A tracer emitted in one region appears after a certain time at a higher altitude over another region. Such vertical and horizontal transport pathways are indicated as $MC_{surf} \rightarrow WP_{14.6\,km}$, $MC_{surf} \rightarrow CP_{14.6\,km}$ and $MC_{surf} \rightarrow EP_{14.6\,km}$. This notation will be extensively used to compare the dominance of different transport pathways in different months. It should be noted that the eastward zonal winds in the TTL form part of the Walker circulation. The descending branch of the Walker circulation is indicated by enhanced $MC_{surf}$ mass mixing ratios between 8 and 12 km at the CP/EP border. We will come back to the influence of the Walker circulation in the discussion of the transport summary below.

In order to identify efficient transport pathways we analyse the mass mixing ratios of all tracers at a representative height in the TTL by constructing an $8 \times 8$ matrix, indicating the emission regions on the x-axis and the receptor regions (at a certain altitude corresponding to one of the three vertical levels defined above) on the y-axis. An example is given in Fig. 3. Each square corresponds to one of the possible transport pathways between the 8 regions defined in our experiment, here for the month of November and for the $Q_{clear} = 0$ level at 14.6 km. Conceptually this methodology is a source-receptor relationship to identify likely pathways from a source region at the surface (x-axis) to receptor regions (y-axis) at a certain altitude. High tracer mixing ratios (dark blue colours) indicate that the transport pathway is relatively efficient (e.g., $MC_{surf} \rightarrow MC_{14.6\,km}$) with lighter colours indicating less efficient transport pathways (e.g., $EP_{surf} \rightarrow SA_{14.6\,km}$). In contrast to Fig. 2, concentrations are now given in percent relative to the near-surface mean, defined as the average tracer concentration of all 8 tracers over all 8 regions at 0.5 km. The boxes on the matrix diagonal indicate vertical transport pathways, while boxes off the diagonal indicate vertical and zonal transport pathways.





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In the next section we use matrices constructed in this way – for four different months in 2005 and for the three characteristic levels in the TTL – to identify the model's preferred transport pathways from the surface to the TTL and their seasonality.

## 3 Patterns of tracer transport through the TTL

Figure 4 compares the matrices at 12.5 km, 14.6 km and 16.9 km (rows, from bottom to top) for all four months (columns). A broad overview of the seasonal and regional variations in mass transport can now be easily seen. The short (30-day) model integrations were designed to highlight fast transport mechanisms (e.g., convective uplift in the boundary layer and the free troposphere) into the TTL; transport driven by the slower, seasonal transport regimes (e.g., radiatively driven ascent) is not captured by our analysis. Consequently, the matrices highlight the modelled pathways which are potentially important for the transport of short-lived surface emitted species into the TTL and directly into the stratosphere. Starting from the base of the TTL, we will next use the matricies in Fig. 4 to discuss the modelled tracer transport, from the surface to the three TTL surfaces, and how they evolve as a function of altitude and season.

### 3.1 Matrices at 12.5 km

In all four months analysed we find a pronounced diagonal, indicating a large local impact on the TTL composition. In February and November the diagonal is slightly less pronounced with lower values over the East Pacific. For most regions there is no marked seasonal cycle in the location of influx of surface emitted tracers into the TTL. In the model, tropical transport from the surface up to the base of the TTL is dominated by large-scale upwelling and detrainment; this level coincides closely with the level of mean tropical convective outflow (see Fig. 2). The results suggest that much of the seasonal variation of short-lived surface emitted species observed in the lower TTL is dominated by the magnitude of emission fluxes (and their longitudinal variation)





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and not by regions of greater convective activity. In contrast, Levine et al. (2007) diagnosed in a chemistry-transport model that short-lived surface tracers preferentially cross the lower TTL boundary (defined at a height around 340 K, ~12 km) over the Maritime Continent where vertical velocities are higher. However, as shown in Russo et al. (2011), that model underestimated the percentage of convective cloud tops reaching above 12.5 km and the height of mean convective outflow, whereas the model used here compares well with observational evidence of high reaching convection (Russo et al., 2011), lending credibility to the transport pattern inferred in Fig. 4.

### 3.2 Matrices at 14.6 km

The strong diagonal seen at 12.5 km weakens at 14.6 km which is about the model's level of mean convective outflow (see Fig. 2 and Hoyle et al., 2011 and the discussions therein). The matrices now highlight these limited regions of deep and frequent convective transport reaching up to and above the $Q_{\text{clear}} = 0$ level. In February and November, the highest mixing ratios originate from the MC, WP and CP regions, whereas in May and August the highest mixing ratios are coming from the IO, MC and WP regions. These tracers preferentially go through the lower part of the TTL in the same broad regions as their emissions (e.g., $\text{MC}_{\text{surf}} \rightarrow \text{MC}_{14.6\,\text{km}}$). Vertical (on-diagonal) transport from the surface up to the upper TTL (above $Q_{\text{clear}} = 0$) dominates over zonal (off-diagonal) mixing on time-scales considered here. In February and November the off-diagonal eastward transport from the $\text{MC}_{\text{surf}}$ and $\text{WP}_{\text{surf}}$, which is associated with the Walker circulation, is highlighted by the dark to light blue colour gradient – i.e., eastward pathways of steadily decreasing mass over the Pacific (e.g. $\text{MC}_{\text{surf}} \rightarrow \text{MC}_{14.6\,\text{km}} \rightarrow \text{WP}_{14.6\,\text{km}} \rightarrow \text{CP}_{14.6\,\text{km}} \rightarrow \text{EP}_{14.6\,\text{km}}$).

### 3.3 Matrices at 16.9 km

As expected, no pronounced diagonal is found, but in February and November relatively high concentrations of the MC and WP tracers are shown indicating some





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regional fast and deep vertical transport (e.g. $MC_{surf} \rightarrow MC_{16.9\,km}$). This pathway is potentially important for VSLS budgets as the Maritime Continent, with its shallow warm coastal waters and high bio-productivity, is a potentially rich source of short-lived brominated species (e.g., Quack, 2004; Warwick et al., 2006; Pyle et al., 2011). As was found at 14.6 km, there is some seasonality associated with the Walker circulation; with off-diagonal enhanced tracer mixing ratios downwind from the source regions during November and to a lesser extent during February (compare 12.5 km matrices and Fig. 2). In contrast, convection is not as deep in May and August as it is in February and November within the 20° N–20° S tropical belt shown by relatively lower mass mixing ratios at 16.9 km.

## 4 Conclusions

The patterns of tropical fast transport pathways, as deduced from the matrices in Fig. 4, highlight regions and seasons of preferential entry of surface-emitted ozone depleting short-lived species into the stratosphere. As shown by Hosking et al. (2010) and Russo et al. (2011), we find that the model used here captures important aspects of convective transport for the analysed non-ENSO year, 2005.

In these model experiments, almost all tropical regions contribute similar amounts of surface emitted tracers through the base of the TTL at the level of the lapse rate minimum (~ 12.5 km). This is shown by pronounced diagonals in the matrices in Fig. 4. Over most regions, above this level, the horizontal component of tracer transport increases as fast vertical transport becomes less efficient. However, in regions of deep convection tracers are still lifted rapidly up to the level of net-zero radiative heating ($Q_{clear} = 0$) in all months analysed. Tracers do reach the tropopause level within 20 to 30 days but only during February and November over the Maritime Continent and the West Pacific. As the tropical tropopause region is colder and drier between November and February (Mote et al., 1996; Newell and Gould-Stewart, 1981; Robinson, 1980), scavenging of halogenated short-lived compounds by ice and liquid water is likely reduced, allowing





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a higher fraction of $Br_y$ to reach the stratosphere then (Sinnhuber and Folkins, 2006). Vertical transport from the surface to the tropical tropopause over Africa and South America is weaker in comparison. This differs from the findings of Liu and Zipser (2005) who reported similar frequencies of convective clouds over-reaching about 14 km over Africa, the Maritime Continent and South America, as diagnosed from satellite measured ice reflectivity. From these data they argue that convective mass transport and the detrainment of tropospheric air above 14 km is comparable across these regions. However, this may well be questionable on two counts. Firstly, it assumes that the formation of ice particles will be similar between the Maritime Continent region (oceanic convection) and the large regions of Africa and South America (continental convection) where the availability of water vapour and latent heat may be somewhat different. Secondly, their analysis does not provide any insight into the mean height of entrainment into the convective towers and so the amount of surface material that will detrain from deep convection in the TTL cannot be quantified.

Our results highlight the importance of the Walker circulation in redistributing MC injected VSLS horizontally in the lower TTL and the possibility of direct regional injections into the lowermost stratosphere (Fig. 2). In February and November, greater upwelling near the West Pacific enhances the Walker circulation and consequently increases downwelling over the East Pacific, suppressing deep penetrating convection and vertical tracer transport in the region. During an El Nino (La Nina) period the upwelling branch of the Walker circulation would be weaker (stronger) as convection shifts eastward (westward). Further work is required to understand the full impact of the Walker circulation variability, its interaction with deep tropical convection and transport of ozone depleting substances which is fundamental for improving future stratospheric chemistry and climate predictions.

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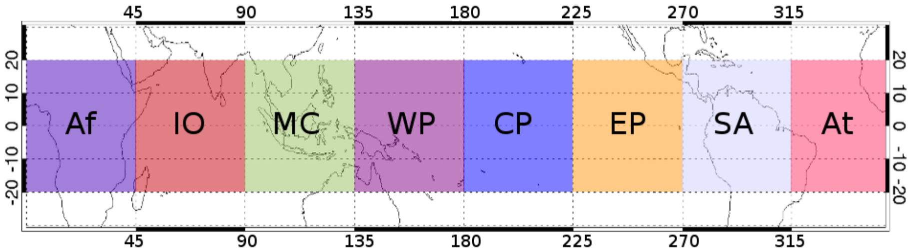


**Fig. 1.** The 8 tropical domains used for seasonal and regional tracer transport analysis. All domains are of equal size of between 20° N–20° S and 45° in longitude.





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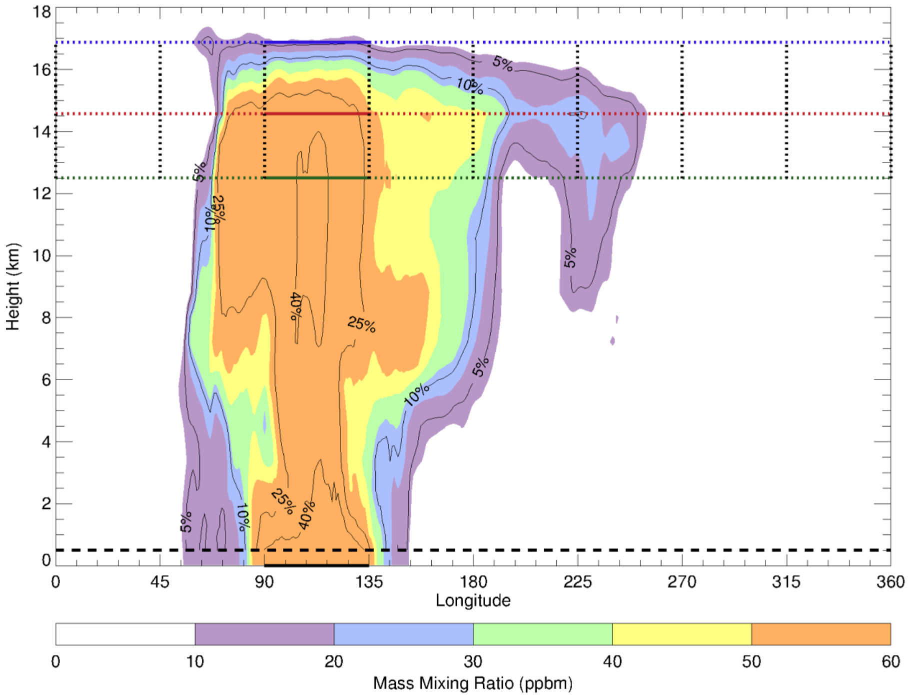


**Fig. 2.** Longitude-height distribution of a surface emitted tracer with an infinite lifetime from the Maritime Continent domain (MC). The tracer distribution is averaged between latitudes 20° N–20° S over the last 10 days in the November integration using (1) mass mixing ratios (shading) and (2) percentages (black contours) relative to the mean mass mixing ratio of all tracers over all regions at 0.5 km (long-dashed black line). The TTL surfaces are here defined by the nearest model levels at 12.5 km (green line), 14.6 km (red line) and 16.9 km (blue line) corresponding to the LRM, $Q_{clear} = 0$ and CPT, respectively.

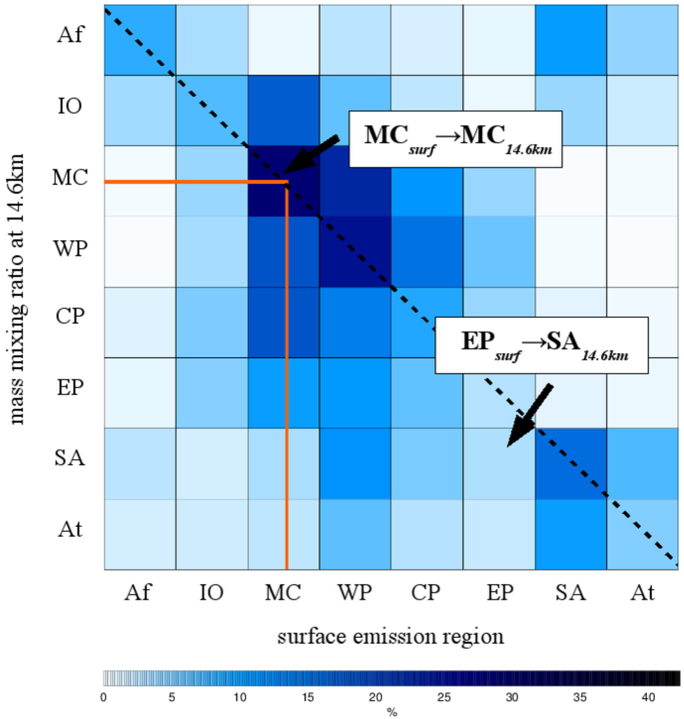


**Fig. 3.** A "surface-TTL" matrix where the boxes represent tropical transport of 8 surface emitted tracers (x-axis) to the same 8 regions (y-axis) at the height of 14.6 km (i.e., near the tropical mean $Q_{clear} = 0$ level) – here shown for the November integration. The relative mean mass mixing ratio (see Fig. 2) in each box is represented by colour intensity in accordance to the range shown by the colour-scale below the matrix. The dotted black line illustrates the boxes where high concentrations would indicate efficient vertical transport of the tracers from their surface regions to 14.6 km.





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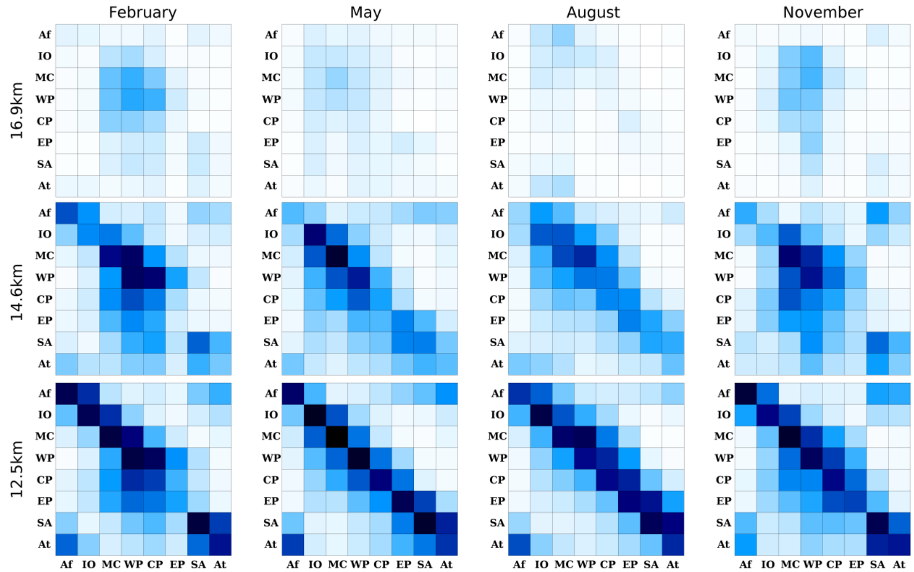


**Fig. 4.** Matrices that represent tropical transport pathways of 8 regional surface emitted tracers (x-axis) to the same 8 regions (y-axis) for 3 levels in the TTL; 12.5 km (LRM), 14.6 km ($Q_{clear} = 0$) and 16.9 km (CPT) – shown by the 3 rows. Results are shown for the mean over the last 10 days for the February, May, August and November 2005 integrations. Darker colours represent high relative mass mixing ratios (see Fig. 2) using the colour-scale from Fig. 3.





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