The impact of cirrus clouds on tropical troposphere-to-stratosphere transport

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Synopsis

We demonstrate that upwelling associated with cirrus clouds offers a path for troposphere-to-stratosphere transport (TST). We show that a combination of deep convection and subsequent upwelling in cirrus clouds and clear sky can explain the supply of air for the Brewer-Dobson circulation.

Introduction

Although it is well known that air enters the stratosphere preferentially through upwelling in the tropics, the exact mechanisms of troposphere-to-stratosphere transport (TST) are still unknown.

Previously proposed mechanisms have been found either to be too slow (e.g., clear sky upwelling) to provide agreement with in situ tracer measurements (Sherwood and Dessler, 2003), or to be insufficient in mass flux to act as a major supply for the Brewer-Dobson circulation (e.g., direct convective transport). In this study we evaluate whether the lofting of air via cirrus cloud-radiation interaction might offer an alternative path for TST.

Radiation & vertical transport

The extratropical pump may dominate the large scale background circulation. On the mesoscale however, radiation plays an active role in driving the tropical upwelling. Whether air masses are efficiently transported upward is determined by their cloud radiative properties relative to the environment.

Therefore, individual air parcels experience radiative heating, not as a balancing process, but as a forcing that determines the actual diabatic ascent or decent rate of individual air parcels.

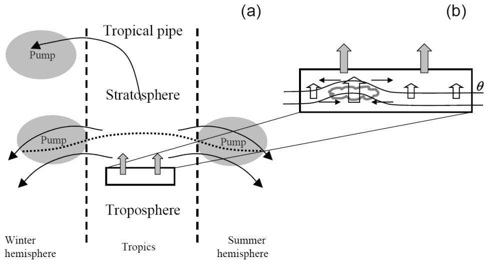

Figure 1: Schematic of tropical large scale upwelling. (a) The mean transport through the tropical cold point tropopause is mainly driven by dissipating waves (see Plumb, 2002). (b) The mesoscale differences in the upwelling velocity are determined by radiative properties of cloudy and cloud free air masses. Specifically, absorption of infrared radiation in upper tropospheric cirrus leads to enhanced upwelling.

Data

Atmospheric profile data: Balloon sonde measurements from different sources have been evaluated to establish a set of vertical temperature, ozone and water vapor profiles with high vertical resolution (Fig. 2). All profiles have been measured between 1998 and 2004.

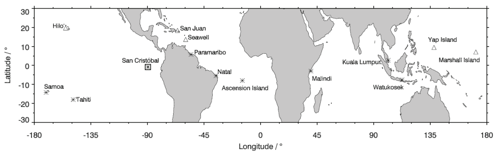

Figure 2: Locations of tropical (20° S to 20° N) balloon sonde measurements used in this study. San Cristóbal, Galapagos Islands (square): 15 simultaneously measured profiles of water vapor, temperature and ozone (Vömel et al., 2002). Tropical Southern Hemisphere Additional Ozonesondes (SHADOZ) network locations (stars): 1,554 simultaneously measured temperature and ozone profiles (Thompson et al., 2003). Tropical NOAA/NCDC radiosonde locations (triangles): 15,880 high resolution temperature profiles.

Cloud data: Information on cloud occurrence and properties from two sources were combined for this study, the ISCCP D1 data (Rossow and Schiffer, 1999) and cloud observations from LITE (McCormick et al., 1993). The International Satellite Cloud Climatology Project (ISCCP) D1 data set provides cloud occurrence statistics from September 1983 to September 2001 based on the analysis of radiance measurements from weather satellites with a spatial sampling resolution of approximately 30 km.

The lack of information on detailed cloud vertical structure is a serious limitation of the ISCCP data for the computation of radiative heating rates. In order to overcome this limitation, we have combined the ISCCP D1 data with measurements from the Lidar In-space Technology Experiment (LITE), a space borne lidar flown on space shuttle Discovery from 10–19 September 1994.

Radiative transfer calculation

The model by Fu and Liou (1992) was used to calculate the radiative heating rates. At each of the 15 balloon sonde locations, full sky heating rate profiles were computed based on all 21,472 cloud extinction profiles combined with randomly selected atmospheric profiles, resulting in more than 300,000 calculations.

The radiative calculations have been evaluated to compute separate mean radiative heating rate profiles for air in clouds and cloud free air (i.e., above and below clouds and in cloud free regions). Mean profiles were calculated at all locations which were then averaged to provide a mean tropical heating rate profile.

Results

Mean profiles of radiative heating rates are depicted in Fig. 3.

- In cloud free air, radiative cooling prevails below 15 km, but radiative heating prevails above (red). Inside of clouds, the transition from cooling to heating occurs at 11.5 km (blue).
- The in cloud radiative heating rates amount to 1 – 2 Kday^{-1} between 350 and 370 K potential temperature. Outflow from deep convection reaching 350 K can therefore be transported into the vicinity of the tropopause in two weeks if it stays inside cirrus clouds for most of the time.

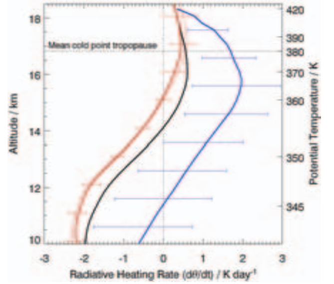

Figure 3: Mean radiative heating rates in the tropics from more than 300,000 calculations, separated for air in clouds (blue) and cloud free air (red). The horizontal bars represent the 25th and 75th percentiles. Also shown is a heating rate profile assuming clear sky (dotted red). The black line represents the full sky heating rates.

Fig. 4 depicts mean vertical radiative mass flux profiles for the radiative heating rate profiles shown in Fig. 3.

- There is a substantial amount of upwelling due to cloud lofting between 12 and 16 km (blue). Above, upwelling in clear sky (red) becomes more important than in clouds.
- A combination of cloud lofting and clear sky upwelling is able to transport the 1 – 2 kgm^{-2}day^{-1} required by the Brewer – Dobson circulation from 350K into the stratosphere.

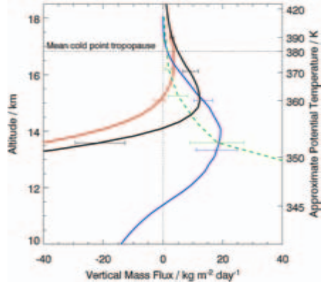

Figure 4: Mean tropical vertical mass fluxes in cloud free air (red) and in clouds (blue) derived from mean radiative heating rates. The black line shows the full sky radiative mass flux. The green dashed curve represents estimated mean tropical convective mass fluxes (Gettelman et al., 2002). The horizontal lines are estimated uncertainties.

Conclusions

- Based on the results presented in the previous section, we conclude that the pathway for TST outlined in Fig. 5, is plausible.
- The estimated transport times agree well with the transport times derived from tracer measurements, namely 60±20 days and 110±30 days on 390 and 420 K, respectively (Boering et al., 1994).

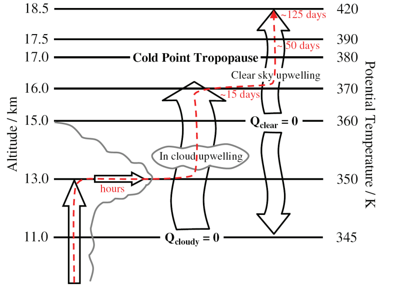

Figure 5: Schematic of troposphere-to-stratosphere transport pathway. Left: Deep convection of moderate strength up to about 350 K. Center: In-cloud upwelling to 370 K. Right: Upwelling in clear sky or in optically in optically very thin cloud through the cold point tropopause into the lower stratosphere. Red numbers indicate typical transport times from the boundary layer to different levels.

Acknowledgments

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