10.8 DIAGNOSES OF THE VERTICAL STRUCTURE OF THE TROPICAL TROPOPAUSE REGION

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1. INTRODUCTION

The tropical tropopause layer (TTL) is a transition layer between the convective equilibrium of the tropical troposphere and the radiative equilibrium of the stratosphere. As reviewed by Holton et al. (1995), the stratospheric circulation is driven by extratropical wave forcing. While anectodal evidence of convection at the tropopause exists, recent work (Gettelman et al., 2001) indicates that such convection is rare. In this work we examine the relative roles of tropospheric convection and large scale diabatic heating at the tropopause and try to define the coupling between the troposphere and the stratosphere.

We find that the level of main convective influence in the upper troposphere is at 10−12km, which we define as the base of the tropopause layer. Above this level, as noted by Folkins et al. (1999), the impact of convection drops off rapidly as air approaches stratospheric stability. The level of maximum convection varies in space and time, which may have important implications for the chemistry of the TTL.

2. THE TROPICAL TROPOPAUSE LAYER

The coupling between the stratosphere and troposphere occurs in the tropopause layer, as the influence of convection tails off. The theoretical basis for the coupling between the stratosphere and the troposphere is illustrated in Figure 1. The top panel presents several different temperature profiles: an isothermal profile (dT/dz=0), an adiabatic profile (dT/dz= Γd, the dry adiabatic lapse rate), and two profiles representative of the stability regimes, a radiative equilibrium taken from Manabe and Wetherald (1967) and a convective equilibrium profile (dθe/dz=0, constant equivalent potential temperature). Note that the combination of a convective equilibrium profile from the surface to the troposphere and a radiative equilibrium profile in the stratosphere (top panel) looks very much like an atmospheric sounding in the tropical western Pacific (Figure 2 top panel).

Furthermore, the potential temperature approaches a constant value in a convective equilibrium profile as all the water is removed (Figure 1 middle panel). Again, the combination of convective equilibrium and radiative equilibrium resembles actual tropical soundings (Figure 2 middle panel). At tropopause levels (15km) the potential temperature lapse rate (temperature lapse rate works just as well), goes to zero in a convective

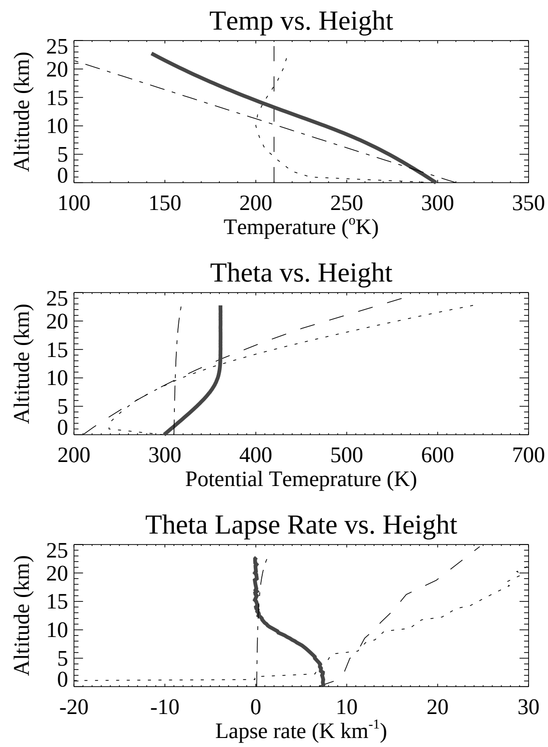

Figure 1: Temperature vs. Height (top Panel), Potential Teperature (Theta) vs. Height (middle panel) and Potential Temperature Lapse Rate vs. Height (bottom panel). Dashed line: sothermal profile (dT/dz=0), Dash−dot line: adiabatic profile (dT/dz= Γd, the dry adiabatic lapse rate), Dotted line: a radiative equilibrium taken from Manabe and Wetherald (1967), Thick solid line: convective equilibrium profile (dθe/dz=0, constant equivalent potential temperature)

profile, but in the radiative profile it increases rapidly (Figure 1 bottom panel). The difference in lapse rate signature provides a clear transition between the stability regimes which can be precisely located. The minimum in the lapse rate profile in the upper troposphere marks the maximum impact of convection. The altitude of this minimum for these soundings is between 10−14km, significantly below the tropopause at 16km (bottom panel of figure 2).

This minimum lapse rate on a profile is the level of the maximum influence of convection, and we will use this to define the bottom boundary of the tropical tropopause region, hereafter the tropical tropopause layer (TTL).

High vertical resolution and long temporal resolution records from radiosondes are available to explore the details and variability of the tropopause region at individual locations. We also illustrate how these

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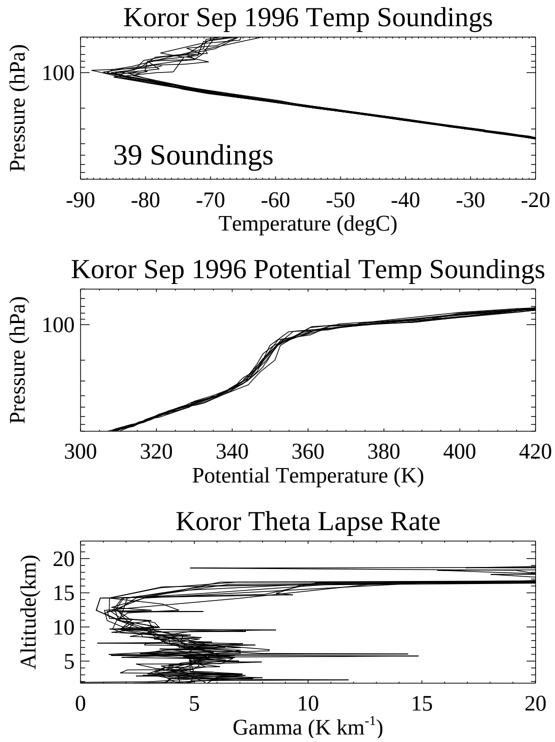

Figure 2: Temperature (top panel), Potential Temperature (middle panel) and Potential Temperature Lapse Rate (bottom panel) profiles from Koror (7N, 134E) for September 1996. Vertical Scale is the same for all panels: marked in pressure in top two and altitude in the bottom panel.

signatures are consistent with observed proxies of convection (Outgoing Longwave Radiation) and the chemical signature of the layer from ozonesondes. Important regional differences are noted in the structure of the TTL, which may affect the coupling of the stratosphere and the troposphere.

3. CLIMATOLOGY OF THE TTL

Using sounding data from 22 selected operational tropical radiosonde stations and ozonesondes from the SHADOZ ozonesonde archive (Thompson and Witte, 1999), we will define the tropopause layer at each station. The upper level of the layer is defined as the cold point tropopause, near 17km in the tropics. The bottom of the TTL is defined as the location of the minimum lapse rate. Operational radiosonde data allow these locations to be discerned with several hundred meter vertical resolution, and thousands of soundings. To supplement these data we will use 100 and 50m vertical resolution soundings of temperature and ozone from the SHADOZ archive. This data will be supplemented with an independent proxy of convective activity; daily Outgoing Longwave Radiation (OLR) data interpolated by the National Oceanic and Atmospheric Administration (NOAA), and provided by the NOAA Climate Diagnostics Center, Boulder, Colorado (http://www.cdc.noaa.gov/).

To validate the use of the minimum lapse rate as the base of the TTL we first use ozone soundings. High vertical resolution soundings from the SHADOZ archive indicate the altitude of the minimum lapse rate lies just below the altitude of the ozone minimum. The ozone minimum is created when convection lofts air with low ozone from the surface into the upper troposphere. Above this level, photochemical production of ozone during slow ascent and mixing with the extratropical stratosphere increase the ozone concentration. These processes led Folkins et al. (1999) to argue for a 'mixing barrier' at the point where ozone begins to increase, above which there is little convective activity.

The signature of convection also supports the interpretation of the minimum lapse rate as the base of the TTL. Analysis of data at operational radiosonde stations shows that the level of minimum lapse rate rises and falls monthly with OLR. The correlation of monthly OLR and altitude of minimum lapse rate is high (0.7−0.9) at all stations. When OLR is low, the height of the lapse rate minimum is high, and vice versa. Stations in each hemisphere show coherent variations, with altitude maxima generally in the summer hemisphere when convection is a minimum. This is indicated in the climatology in Figure 3. Note that for all stations the change in height of the cold point tropopause has the same seasonal cycle between hemispheres, higher in January than in July. This seasonal cycle is that expected from the stratospheric residual circulation (Holton et al., 1995). The seasonal cycle of the lower boundary of the TTL, the minimum lapse rate, is not consistent between regions. The western Pacific, central Pacific and Indian regions have more stations in the southern hemisphere, so that the average altitude of the minimum lapse rate is higher in SH summer (December−February) when convection is active. However, 3 of 4 stations over Africa are in the northern hemisphere, with strong convection in April−June. Finally, over South America there are stations spread throughout the tropics, including along the equator, so that a double peak is seen in spring and fall as convection crosses the equator. Thus the seasonal variability in the altitude of the minimum lapse rate is controlled by local convective processes.

Furthermore, analysis of interannual variations of the base height of the TTL illustrates significant correlations with convective activity. For stations in the western Pacific, the height of the lapse rate minimum is anomalously low during El−Nino warm events when convection moves out into the central Pacific, and it is anomalously high during La−Nina cold events when convection is concentrated in the western Pacific. In the central Pacific anomalies have the opposite correlation with El−Nino, as expected from anomalies in convection. All these factors indicate that the height of the minimum lapse rate is a good indicator of convective activity.

The overall climatology of the TTL from these analyses is illustrated in Figure 3, for several stations averaged over each region of the globe. The cold point tropopause height is virtually the same across the

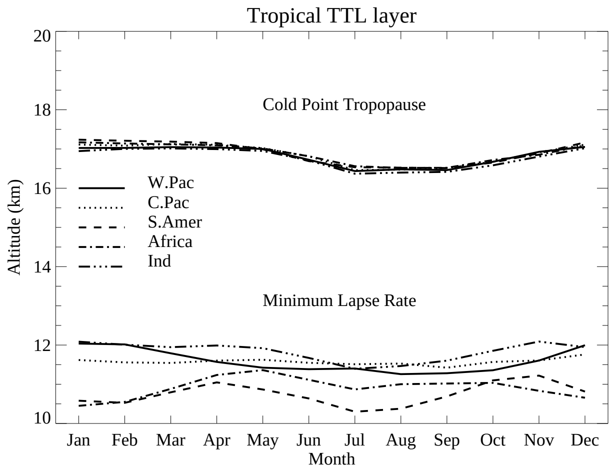

Figure 3: Tropical Tropopause Layer averaged in 5 different regions as a function of altitude and month. Western Pacific (solid line), Central Pacific (dotted line) South America (dashed line), Africa (dot−dash line) and Indian Ocean (dot−dot−dash line).

globe, consistent with non−local control by the stratospheric circulation. At the lower level of the TTL, the level of the minimum lapse rate, there are important zonal variations on top of the seasonal variations between regions noted above (which arise due to the distribution of stations in longitude). There are consistent differences of nearly 2km zonally across the tropics in the height of the TTL base, diagnosed from the maximum influence of convection. The minimum lapse rate is highest over the western and central Pacific, slightly lower over the Indian ocean, and 1−2km lower (depending on season) over Africa and South America. Analysis of ozonesonde data in the southern hemisphere tropics confirms that the minimum value of ozone is 50% lower (20−30 ppbv vs. 40−60 ppbv) in the western Pacific than over S. America or Africa, indicating that this zonal difference extends to the chemical signature as well.

4. IMPLICATIONS FOR STRAT−TROP COUPLING

The implications of the structure of the TTL for stratosphere−troposphere coupling are important. It appears that the height of the TTL is generally at 10−12km, which is about 5−7km below the cold point tropopause. Some convection does get up to the tropopause, but air in the TTL must be strongly affected by radiative heating which tends to loft air slowly and make the air more stable. These results are confirmed by the distribution of surface equivalent potential temperature (Folkins et al., 2000) which peaks near 345 K. The 345 K potential temperature isentrope is located around 10−12km in the tropics, in good agreement with Figure 3. The equivalent potential temperature at the surface is the potential temperature level of the level of neutral buoyancy assuming undiluted ascent. This also provides an explanation for the regional differences in the TTL. The differences are a function of the distribution of equivalent potential temperature at the surface, which is higher over the warm waters of the tropical Pacific, and lower (on average) over tropical continents, which have a reduced supply of moisture.

Different altitudes of injection of air into the TTL imply that air from the Pacific may spend less time in the TTL (radiative heating being equal) before entering the stratosphere than air lofted in convection over South America or Africa. This might be expected to have a significant effect on the chemical signature of air entering the stratosphere. For example, the products of biomass burning over Africa or South America may not be lofted as readily into the stratosphere as air over Indonesia. We might expect the seasonal cycle of ozone and carbon monoxide for example to show some evidence of this regional variation of convective influx into the tropopause layer.

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