Tropical convective outflow and near surface equivalent potential temperatures

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Short title: TROPICAL CONVECTIVE OUTFLOW AND NEAR SURFACE $\theta_E$
Abstract. We use clear sky heating rates to show that convective outflow in
the tropics decreases rapidly with height between the 350 K and 360 K potential
temperature surfaces (or between roughly 13 and 15 km). There is also a rapid fall-off
in the pseudoequivalent potential temperature probability distribution of near surface
air parcels between 350 K and 360 K. This suggests that the vertical variation of
convective outflow in the upper tropical troposphere is to a large degree determined by
the distribution of sub cloud layer entropy.
Subcloud layer entropy plays an important role in determining the depth of convective mixing in the tropics [Emanuel, 1994]. Figure 1 shows two probability distributions of “near surface” pseudoequivalent potential temperature $\theta_e$ in the tropics. $\theta_e$ is a measure of entropy which includes the potential contribution arising from water vapor condensation. Its virtue in this context is that the $\theta_e$ of an air parcel is approximately conserved during upward transport within clouds provided there is no mixing. The cumulative probability distribution $N(\theta_e)$ shown in Figure 1 gives the fraction of air parcels below 1 km whose pseudoequivalent potential temperature is larger than a given $\theta_e$. Approximately 7% of the air parcels below 1 km in the tropics have a $\theta_e$ larger than 355 K. The curve $dN(\theta_e)/d\theta$ is the relative probability distribution of near surface $\theta_e$ obtained by counting the number of $\theta_e$ measurements in 1 K bins. It has been normalized so that its largest value is equal to 1. There is a rapid (roughly exponential) decrease in the occurrence of air parcels with $\theta_e$ larger than 355 K.

The distribution shown in Figure 1 is intended to represent an annual tropical average. It was compiled from temperature and humidity profiles from the following missions: the Pacific Exploratory Mission (PEM) - Tropics A and B, the Indian Ocean Experiment (INDOEX), and the Southern Hemisphere Additional Ozonesondes (SHADOZ) initiative. For simplicity, we will collectively refer to this dataset as the SHADOZ archive. It involved a total of 673 profiles - 93 from Ascension Island (8°S), 4 from Christmas Island (2°N), 77 from San Cristobal (1°S), 114 from Fiji (18°S), 23 from Watukosek Java (7.5°S), 53 from Kaashidhoo (5°N), 94 from Nairobi (1.3°S), 40 from Natal (5.4°S), and 175 from Samoa (14.2°S). The average latitude, weighted by
the number of profiles, was 8.3 °S. There was an approximately equal number of sondes taken in each season. Since the sondes were taken at varying vertical resolution, a $N(\theta_e)$ was first calculated for each site, and then entered into the overall average in a weighted manner depending on the number of sondes at that site. Pseudoequivalent potential temperatures were calculated using the Bolton parameterization [Bolton, 1980].

The two main mechanisms which drive downward descent across isentropic surfaces in the tropics are radiative and evaporative cooling. The radiatively driven mass flux $M_r(\theta)$ can be approximated as

$$M_r(\theta) = \rho(\theta) w_r(\theta) = \rho(\theta) Q(\theta) \left( dT(\theta)/dz + \Gamma_d \right).$$

Here $dT(\theta)/dz$ is the derivative of temperature with respect to height, $\Gamma_d$ the dry adiabatic lapse rate, $\rho(\theta)$ density, $w_r(\theta)$ the downward radiative velocity, and $Q(\theta)$ the clear sky radiative cooling rate. This expression is valid in clear-sky regions over long timescales where the heights of potential temperature surfaces can be regarded as fixed.

The left hand side of Figure 2 shows the vertical variation of $M_r(\theta)$ in the upper tropical troposphere obtained from (1). The open circles represent the mass flux $M_r(\theta)$ while the solid circles represent $N(\theta_e)$, with in this case, the vertical axis understood to be $\theta_e$ rather than $\theta$. The horizontal axes of $M_r(\theta)$ and $N(\theta_e)$ have been adjusted so that the two plots roughly coincide at $\theta = 348$ K. This has been done to emphasize that $M_r(\theta)$ and $N(\theta_e)$ are roughly proportional to one another for $\theta$ (or $\theta_e$) larger than 345 K.

The simplest way to explain the scaling between $M_r(\theta)$ and $N(\theta_e)$ shown in Figure...
2 is to assume (1) that near surface air parcels have a roughly equal probability of being subjected to deep convection, (2) that air parcels detrain from convective systems near their Level of Neutral Buoyancy (LNB), (3) that most of the downward descent in the tropics is driven by radiative cooling, and (4) that the radiative effect of clouds on the vertical mass flux is small. Although none of these assumptions can be expected to be correct in any exact sense, they may be sufficiently valid, at least above 345 K, to account for the scaling between $M_r(\theta)$ and $N(\theta_e)$ in this region.

The right hand side of Figure 2 shows that the vertical divergence of the radiatively driven mass flux, $dM_r(\theta)/dz$, roughly scales with the relative near surface $\theta_e$ probability distribution $dN(\theta_e)/d\theta_e$. This follows from the scaling between $M_r(\theta)$ and $N(\theta_e)$ and is shown for illustrative purposes. The divergence of $M_r(\theta)$ can be regarded as approximately equal to that part of the convective outflow which is driven by radiative cooling. $dM_r(\theta)/dz$ decreases somewhat less rapidly with height than does $dN(\theta_e)/d\theta_e$ for $\theta$ higher than 355 K. This would be consistent with a somewhat greater likelihood for deep convection in regions of higher near surface $\theta_e$.

A three-dimensional modeling simulation gives the net mass flux at 10 km as approximately 0.004 kgm$^{-2}$s$^{-1}$, or 345 kgm$^{-2}$day$^{-1}$ [Tompkins and Craig, 1998]. Net mass flux in this case refers to the residual between the mass fluxes from convective updrafts and downdrafts, and should approximately equal $M_r$ at 10 km, which from Figure 2 is about 350 kgm$^{-2}$day$^{-1}$. The manner in which modeled mass fluxes decrease with height above 10 km should be quite sensitive to their near surface $\theta_e$ distributions.

The clear-sky heating rates used in (1) were calculated using a radiative transfer
model based on the $\delta$-four-stream method [Fu and Liou, 1992]. The annual tropical climatologies of temperature, water vapor, ozone, and pressure at 0.5 km resolution used in the model was obtained from the SHADOZ archive. Because of uncertainties in the accuracy of water vapor measurements above 12 km, we imposed a constant 3.8 ppmv water vapor mixing ratio above 17 km [Dessler, 1998], and used spline interpolation to determine the relative humidity between 12 and 17 km.

The climatological temperature and lapse rate profiles used in the radiative transfer model are plotted versus $\theta$ in Figure 3. It is interesting that the onset of scaling between $M_r(\theta)$ and $N(\theta)$, the peak of the near surface $\theta_e$ relative probability distribution, and the onset of an increase in lapse rate all occur between 345 and 350 K. By 370 K, the convective outflow (as diagnosed from the radiative mass flux) and the near surface $\theta_e$ relative probability distribution have essentially diminished to zero. This is below both the cold point (383 K) and lapse rate (375 K) definitions of the tropical tropopause, and is consistent with previous work based on GCM's [Thuburn and Craig, 1997], cloud top temperatures [Highwood and Hoskins, 1998], and ozone and lapse rate variations [Folkins et al., 1999], that the traditional definitions of the tropical tropopause are not good indicators of the upper limit of convective mixing in the tropics.

Temperatures in the lower tropical stratosphere are lowest during Northern Hemisphere winter when the adiabatic cooling induced by upward ascent is strongest [Yulaeva et al., 1994]. Tropospheric temperatures above Samoa ($14^\circ$S) are highest during Northern Hemisphere winter when the local solar insolation is strongest. In Figure 4, we have subtracted the average July-September (local winter) temperature
profile above Samoa from the average January-March (local summer) profile. The transition from tropospheric (positive temperature difference) to stratospheric (negative temperature difference) control occurs at 355 K, the approximate altitude at which the convective outflow shown in Figure 2 has diminished to half its maximum value.

Near surface $N(\theta_e)$ distributions at sites within the Western Pacific Warm Pool can be shifted by up to 5 K to the right of the tropical average shown in Figure 1. The scaling between $N(\theta_e)$ and $M_r(\theta)$ is a statistical relationship that can be expected to apply only over sufficiently long times and large distances. It would be interesting to see if the regional and seasonal variations of $N(\theta_e)$ and $M_r(\theta)$ coevolve in a manner consistent with the scaling shown here for tropical means.

There are several indications that water vapor concentrations in the stratosphere have increased over the past several decades [Oltmans and Hofmann, 1995]. This development may have important climate implications [Forster and Shine, 1999]. One explanation is that tropopause cold point temperatures have increased in response to surface warming [Kirk-Davidoff et al., 1999]. Predicting the manner in which cold point temperatures will respond to global warming is made difficult by the fact that it is near a transition from radiative-convective (troposphere) to near radiative (stratosphere) equilibrium. Temperatures in the upper tropical troposphere may respond to surface warming in such a way as to maintain the scaling between upper tropospheric mass fluxes and the near surface $\theta_e$ distributions shown in Figure 2. If so, these constraints may give some insight into how temperatures in this important transition region can be expected to evolve.
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Figure 1. Two probability distributions of near surface (below 1 km) $\theta_e$ values in the tropics. $N(\theta_e)$ is the cumulative probability distribution representing the fraction of air parcels whose $\theta_e$ is larger than a given value. $dN(\theta_e)/d\theta$ is the relative probability distribution obtained by counting the number of $\theta_e$ measurements within a given $\theta_e$ interval, in this case 1 K. The peak of this distribution has been arbitrarily normalized to 1. Both distributions were obtained from the SHADOZ archive.

Figure 2. (left) The curve with open circles is the clear sky vertical mass flux $M_r(\theta)$ as obtained from (1) in the text. The curve with solid circles is $N(\theta_e)$ from Figure 1, but with the axes interchanged. (right) The curve with open circles is $dM_r(\theta)/dz$. The curve with solid circles is $dN(\theta_e)/d\theta$, also from Figure 1 with the axes interchanged.

Figure 3. Temperature and lapse rate (here $dT/dz$ rather than $-dT/dz$) versus potential temperature, from the SHADOZ archive. The lapse rate tropopause is usually defined as the altitude at which temperature decreases less rapidly than 2 K/km.

Figure 4. Local Summer (January through March) minus local winter (July through September) temperatures above Samoa.
Figure 1

N(\theta_e)

dN(\theta_e)/d\theta_e

10^{-1}

10^{-2}

10^{-3}

330 335 340 345 350 355 360 365 370

\theta_e (K)
Figure 2

The figure illustrates the relationship between temperature ($\theta$ or $\theta_e$) and various parameters:

- $N(\theta_e)$
- $dN(\theta_e)/d\theta_e$
- $M_r(\theta)$
- $dM_r(\theta)/dz$

The axes are labeled as follows:

- $\theta$ or $\theta_e$ (K)
- $M_r$ (kgm$^{-2}$day$^{-1}$)
- $dN(\theta_e)/d\theta_e$
- $dM_r(\theta)/dz$ (kgm$^{-3}$day$^{-1}$)

The data points are plotted as circles and dots, with the corresponding lines indicating the trend.
Figure 3

The graph illustrates the relationship between potential temperature and lapse rate with temperature. The Cold Point Tropopause is marked by a downward curve, while the Lapse Rate Tropopause is indicated by an upward curve. The graph shows the temperature range from 300 to 400 K and the lapse rate from -8 to 6 K/km.
Figure 4

Summer minus Winter

Temperature (K)

\( \Theta (K) \)