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22-Year survey of tropical convection penetrating into the lower stratosphere

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[1] A 22-year survey of tropical convection penetrating into the stratosphere has been conducted using special subsets of the International Satellite Cloud Climatology Project cloud data set. In addition to refined information about the geographic distribution of penetrating convective systems, these results show that penetrating convection occurs predominantly in the larger, organized, mesoscale convective systems, whereas smaller, unorganized convective systems rarely penetrate. Durations of penetrating events are longest for the largest systems, hurricanes and typhoons, generally exceeding one day. **Citation:** Rossow, W. B., and C. Pearl (2007), 22-Year survey of tropical convection penetrating into the lower stratosphere, *Geophys. Res. Lett.*, *34*, L04803, doi:10.1029/2006GL028635.

1. Introduction

[2] Deep convection penetrates into the upper troposphere and lower stratosphere, injecting water-vapor-rich, ozone-poor air from near the surface and displacing water-vapor-poor, ozone-rich air downward. In a review of the controlling influences on this part of the atmosphere, *Holton et al.* [1995] conclude that the large-scale stratospheric circulation and chemical transports are dominated by the large-scale-wave-induced circulation but that deep convection can still play a role by conditioning the properties and composition of the air that enters the tropical upper troposphere, lower stratosphere [cf. *Sherwood and Dessler*, 2000]. In fact, where the troposphere ends and the stratosphere begins is somewhat ambiguous in tropical latitudes since there is an extensive layer of nearly constant temperature rather than a sharp transition from negative to positive lapse rate with height [e.g., *Seidel et al.*, 2001]. This region is referred to as the tropical tropopause layer (TTL) and its structure may result, in part, from the vertical variation of mixing induced by penetrating convection [*Dessler*, 2002]. Nevertheless, cloud tops colder than the cold-point tropopause (TT) are conventionally taken to be in the lowermost stratosphere. Although it is now clear that deep convection injects the properties of the near-surface atmosphere, particularly water vapor, into the upper troposphere [e.g., *Sassi et al.*, 2001; *Salby et al.*, 2003; *Luo and Rossow*, 2004] and possibly the lower part of the TTL [*Sherwood and Dessler*, 2003], the situation above that is still ambiguous. The effect of deep convection on the water vapor abundance at these levels depends on the relative humidity of the environment into which the convection detrains and the amount of ice detrained. If the relative humidity is below saturation, then deep convection that detrains a significant amount of ice moistens the layer, but deep convection with little condensate that penetrates above the cold point injects air at lower-than-ambient temperatures thereby helping to maintain subsaturated conditions [*Danielson*, 1993]. On the other hand, if the relative humidity is above saturation, as appears to be common in the upper troposphere near the tropopause [*Jensen et al.*, 2001a], injection of ice can dehydrate the environment [*Jensen et al.*, 2001b]. The fact that the amount of ice near the tops of deep convective clouds is significantly different over land than ocean [*Zipser et al.*, 2006] may mean that the effects on humidity of land and ocean deep convection are also different.

[3] One step towards understanding what role penetrating convection plays in determining the characteristics of the near-tropopause part of the tropical atmosphere is to survey the frequency of occurrence of such events, their geographic, seasonal and diurnal distribution, the details of the cloud-top height distribution and the nature of the convective systems that produce such penetrations. Previous surveys using satellite infrared radiances sensitive to cloud-sized particles [e.g., *Zhang*, 1993; *Gettelman et al.*, 2002] and satellite microwave radiances sensitive to precipitation-sized particles [*Liu and Zipser*, 2005] have already described the geographic distribution and the diurnal and seasonal variations. We add to this information by examining the characteristics of the convective systems that produce the penetrating motions.

2. Analysis Approach

[4] We performed our survey using two different subsets produced from the 22-year long record of the International Satellite Cloud Climatology Project (ISCCP) DX data set [*Rossow and Schiffer*, 1999]. The ISCCP DX data set is produced by analysis of infrared (IR) and visible (daytime only) radiances from weather satellite images with pixels about 5 km across on average, sampled at about 30 km and 3 hr intervals. Although sampled to 30 km spatial interval, the statistics obtained from this data set converge to those obtained from the full 5 km data set if the sample population size is large enough [*Seze and Rossow*, 1991]. For deep convection, which occurs only about 5% of the time in the tropics, seasonal mean values are adequately determined by the ISCCP data set [*Rossow and Cairns*, 1995]. The first subset (the CL data set) is created by identifying "cloud clusters" as all spatially-adjacent pixels in each satellite image with cloud properties beyond some threshold; here we use the set defined by cloud top temperatures (assuming

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clouds are black-body emitters) <245 K (see *Machado et al.* [1998] for discussion of the effects of using different thresholds). Even isolated single pixels that are cold enough are retained as cloud clusters; hence, even single-pixel convective clouds are included. Since the cloud top temperature is retrieved from the infrared brightness temperature by removing atmospheric effects and assuming that the clouds are black-body emitters, results can be obtained day or night; but the thinnest cirrus clouds that may be associated with the convection are excluded from the cloud clusters. This fact is important because there is a class of cloudy pixels in the DX data set that might be mistaken for penetrating convective clouds, if the transmission-corrected cloud top temperatures are used: these daytime cloudy pixels appear to be so optically thin that the ISCCP procedure for correcting cloud top temperatures to account for transmitted infrared radiation fails, in which case the clouds are assigned a top temperature 5 K colder than the tropopause. The 245 K threshold on the black-body cloud top temperature excludes these pixels. The second subset (the CT data set) is produced from the CL data set by tracking the motions of the larger (areas corresponding to circles with radii >90 km) cloud clusters from image to image (the smaller ones are excluded because they do not last more than the 3 hr interval between images) to determine their evolution [*Machado et al.*, 1998]. In the CT subset, a cloud cluster is referred to as a convective system (CS) if, at least once in its lifetime, there is a convective cluster (CC) present within it; a CC is indicated by the presence of at least one pixel with a black-body cloud top temperature <220 K. The CT data set is available at http://isccp.giss.nasa.gov/cgi-bin/CT.pl for the period July 1983 through June 2005. The CL data set will be made available within the next few months.

[5] Penetrating convection is then identified by a minimum (black-body) cloud top temperature, TMIN, within a convective system that is less than the cold point tropopause temperature, TT, taken from the NOAA operational analysis of the HIRS/MSU temperature sounding systems (TOVS) (*Seidel et al.* [2001] show that the cold point and lapse rate tropopause locations are about the same.) Since TMIN may be biased low by a few degrees by transient cooling of rapidly rising air parcels that does not accurately indicate altitude (although IR radiances arise from just below true cloud tops, so this effect is nearly offset) and TT is uncertain given the coarse vertical resolution of the TOVS temperature profiles, the absolute frequency of penetrating convection reported here is uncertain. If we change the threshold on TT-TMIN from 0 to 3 K, representing an estimate of the uncertainty magnitude, the frequencies decrease by about a quarter; however, only the number of penetrating systems changes, not the spatial-seasonal patterns and vertical distributions. We have also considered results obtained by defining penetrating convection by TMIN <200 K, which is approximately the level of neutral buoyancy where the clear sky net radiation changes over from cooling below to warming above – this level is taken to be the bottom of the TTL, which contains the cold point tropopause [*Sherwood and Dessler*, 2000]. Generally, this definition increases the number of penetrating events by an amount similar to that produced by changing the temperature threshold. We focus our attention on penetration into the lower stratosphere defined by TT-TMIN > 0.

3. Results

[6] Figure 1 shows the distributions of seasonal mean TT and instantaneous TMIN < 245 K over lower latitudes (±45°) for the whole 22-year record (1983-2005). The characteristically larger seasonal variability of TT outside the tropics is apparent. In general, the frequency of TMIN occurrence decreases as the value of TMIN decreases [cf. *Gettelman et al.*, 2002], with only a small population of cloud tops above the mean cold point tropopause level (we actually compare TMIN with daily values of TT, which vary about the seasonal mean values by about 4 K rms, about the width of the temperature intervals in Figure 1). The population of TMIN values colder than the tropopause also decreases strongly with latitude even though the mean value of TT increases. In the tropics the TMIN frequency distribution exhibits a peak at about 215 K just below the bottom of the TTL, indicating that most of the tropical deep convection does not enter even the TTL; but there is a secondary peak at the bottom of the TTL at around 200 K. If we focus on only the larger, longer-lived CS, we find that they are responsible for this secondary peak. That is, it is predominantly the organized mesoscale convective systems that produce almost all of the penetrating convection. We find that about 2% of the deep convection penetrates the TTL (*Gettelman et al.* [2002] report a frequency of 0.5% but also show that their use of a data set with 50 km “pixels” underestimates the frequency of occurrence of cloud tops <200 K by more than a factor of two when compared with results obtained using 8 km pixels) and about 1% penetrates into the lower stratosphere.

[7] The seasonal and geographic distribution of penetrating convection (not shown), whether defined by TMIN < TT or TMIN < 200 K, is very similar to that shown by *Gettelman et al.* [2002] and other studies using satellite infrared radiances, indicating that interannual variations in these patterns are not very large. The tropical distribution exhibits five concentrations of penetrating convection – over the maritime continent (east Indian and west Pacific Oceans), in the western end of the South Pacific Convergence Zone and in the eastern end of the Pacific Intertropical Convergence Zone, and over South America and Africa – that are closely associated with slightly colder tropopause temperatures. The largest frequency of occurrence by far appears over the western Pacific – Indian ocean sector rather than over the tropical land areas [cf. *Gettelman et al.*, 2002] where the convective updrafts are much stronger; however, the total number of penetrating convective events is actually slightly larger over land than ocean when normalized by area, especially for penetration defined by TT > TMIN. *Liu and Zipser* [2005] find higher peak frequencies of occurrence over land than ocean for penetrating convection detected by the TRMM radar and microwave radiometer, both sensitive to precipitation-sized ice particles rather than to the much smaller cloud particles detected by IR radiances. *Zipser et al.* [2006] argue that this difference can be understood to be consistent with much stronger convective updrafts over land (much more frequent lightning, larger rainfall intensities) that loft the larger ice

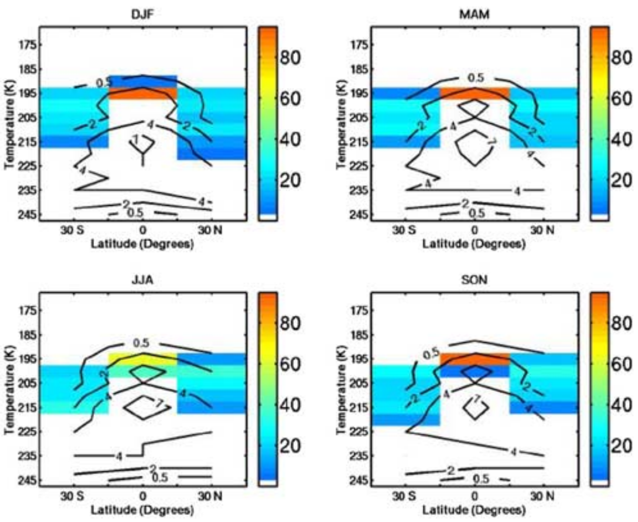

Figure 1. Frequency (in percent) of the zonal, seasonal mean tropopause temperatures (TT in Kelvins) for the four seasons versus latitude (in color, where the percentages add to 100 in each latitude zone) from the operational satellite sounder product (TOVS) and the zonal, seasonal mean frequency (in percent) of the minimum cloud top temperatures (TMIN) in convective systems (CS) from the ISCCP data set (superimposed contours, where the percentage is of all satellite pixels over the whole zone).

particles nearer to cloud tops than do the much smaller updrafts in oceanic convection (much less frequent lightning, smaller rainfall intensities). Despite the difference in updraft strength, there are more frequent penetrations to higher (colder) levels over ocean than over land, which is consistent with differences in the vertical profiles of static stability over ocean and land [cf. *Lucas et al.*, 1994].

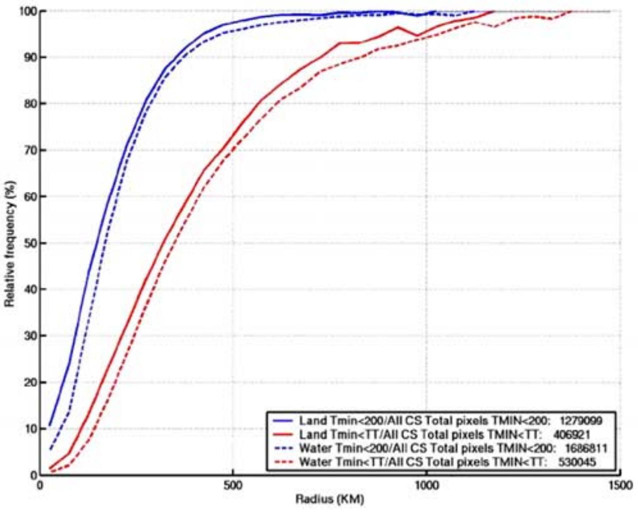

Figure 2. Fraction (in percent) of all tropical convective systems (CS defined by TMIN < 220) in each size range that include penetrating convection over land (solid) and ocean (dashed); blue lines are for penetration determined by TMIN < 200 K and red lines are for penetration determined by TMIN < TT. The minimum size systems included have radii of 37 km; only about 5% of all cloud clusters are smaller CS and much less than 1% of these penetrate the TTL.

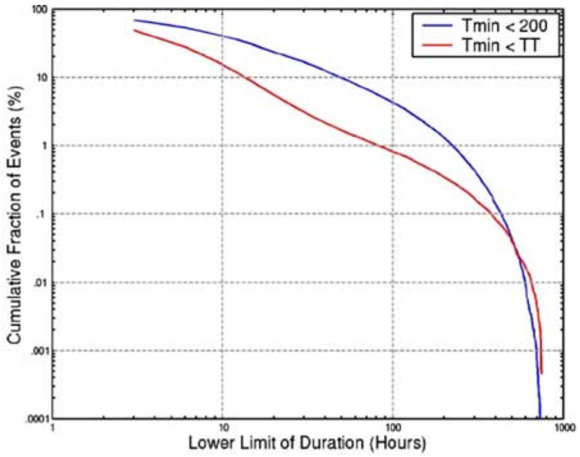

Figure 3. Cumulative fraction (in percent) of all penetrating events in tropics determined by TMIN < 200 K (blue) and TMIN < TT (red) that have event durations (in hours) longer than the value on the abscissa.

[8] The main new results that we add to previous results are shown in Figures 2 and 3. Figure 2 shows the size distribution (truncated at 37 km radius) of tropical CS that include penetrating convection (defined two ways), normalized by the size distribution for all tropical convective systems in the ISCCP CL data set, separately for land and water. There is a notable monotonic increase in the fraction of penetrating systems as the size of the CS increases (note that the majority by number of cloud clusters are very small [cf. *Machado et al.*, 1998], about 75% being smaller than 37 km radius but less than 5% of these have cloud top temperatures cold enough to classified as deep convective). There is a corresponding tendency for TMIN (maximum optical thickness) values to decrease (increase) with increasing CS size [cf. *Fu et al.*, 1990; *Machado and Rossow*, 1993] suggesting that penetrating CS are more vigorous storm systems than typical, consistent with the interpretation by *Zipser et al.* [2006]. In the tropics, almost all CS with radii >500 km contain convection that penetrates into the TTL; almost all CS with radii >1000 km penetrate above TT. The fraction of CS in each size range below 1000 km that contain penetrating convection is slightly larger over land than ocean. Only about 10% of the smallest convective systems penetrate into the TTL but almost no small, isolated convective systems penetrate into the lower stratosphere. For the most extreme case of single-pixel cloud clusters (about 5 km across), only about 0.05% penetrate into the TTL. There are also some notable differences in the fraction of penetrating CS in different longitude sectors (not shown). Our results also show that the penetrating event occurs most frequently at the beginning of the development of the CS; hence, these penetrating events are concentrated more in the morning over oceans and more in the afternoon, early evening over land, as found by *Gettelman et al.* [2002]. Figure 3 shows the cumulative fraction (in percent) of penetrating events with durations longer than a specific length. Since they occur preferentially in the larger, longer-

lived CS, we find that the penetrating events last for a substantial fraction of a day. Notably, several percent of the CS with penetrations have durations exceeding one day: these larger systems are hurricanes and typhoons, which always penetrate above the tropopause. Hence the role of these tropical storms in troposphere-stratosphere exchanges should be examined more carefully, since, although rare, they may dominate the stratosphere-troposphere exchanges, but they have not been investigated by field studies.

[9] Like previous IR-based results, we find that the peak frequency of occurrence of penetrating convection occurs over oceans. This result does not change whether we use a threshold relative to the tropical cold point tropopause temperature or an absolute temperature threshold (representing the base of the TTL), despite the close association between colder tropopause temperatures and more frequent penetrating events. However, if the total number of penetrating convection events is normalized by area, then there are slightly more over land than ocean. As judged by cloud top temperatures, ocean CS penetrate slightly higher than land CS, in contrast with the height reached by precipitation-size ice [*Liu and Zipser*, 2005]. Penetrating events in the CS of the same size are slightly more common over land than ocean. The key new result is that penetration of tropospheric properties into the stratosphere is dominated by the larger, longer-lived, extreme tropical storms, which suggests that the stratosphere-troposphere exchanges and the properties of the stratosphere will vary very intermittently making it difficult to obtain adequate statistics unless long-term data records are used.

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