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Overshooting convection in tropical cyclones

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[1] Using infrared satellite imagery, best-track data, and reanalysis data, tropical cyclones are shown to contain a disproportionate amount of the deepest convection in the tropics. Although tropical cyclones account for only 7% of the deep convection in the tropics, they account for about 15% of the deep convection with cloud-top temperatures below the monthly averaged tropopause temperature and 29% of the clouds that attain a cloud-top temperature 15 K below the temperature of the tropopause. This suggests that tropical cyclones could play an important role in setting the humidity of the stratosphere. **Citation:** Romps, D. M., and Z. Kuang (2009), Overshooting convection in tropical cyclones, *Geophys. Res. Lett.*, *36*, L09804, doi:10.1029/2009GL037396.

1. Introduction

[2] Due to the moist ascent regions within tropical cyclones (TC's), it is reasonable to suspect that deep convective plumes in TC's are not subject to the same amount of entrainment drying found in other mesoscale systems. This leads to the conjecture that a disproportionate number of the deep convective plumes in a tropical cyclone may retain the equivalent potential temperature needed to overshoot the tropopause and penetrate deep into the stratosphere. It is already well known that tropical cyclones alter the humidity of their local environment by, for example, moistening the upper troposphere [*Ray and Rosenlof*, 2007] and possibly drying the lower stratosphere [*Danielsen*, 1993]. The frequency with which TC's punch into the stratosphere dictates how significant their local stratospheric effects are on the global budget of stratospheric water vapor. It is the objective of this study to quantify the fraction of tropical overshooting cloud that is associated with tropical cyclones and to ascertain whether deep convection in TC's has a higher than average chance of penetrating the stratosphere.

[3] At least two previous studies have tried to quantify the contribution of tropical cyclones to overshooting convection. One such study, by *Rossow and Pearl* [2007], used the Convective Tracking (CT) database of Convective Systems (CS) [*Machado et al.*, 1998], where a CS is defined as contiguous cold cloud. *Rossow and Pearl* [2007] suggested that convective overshooting in the tropics occurs preferentially in large CS, where the size of a CS is defined in terms of an effective radius equal to $\sqrt{\text{area}/\pi}$. They further speculated that these large systems are hurricanes and typhoons, thereby demonstrating a dominant role for TC's in troposphere-stratosphere exchange. To check whether these large CS really are tropical cyclones, we have compared the 3-hourly CT data with the National Climatic Data Center's (NCDC) 3-hourly best-track data from the beginning of July 1983 through to the end of November 2004. For every CS, we declare a match with a tropical cyclone if the center of the CS is within 1,000 km of a TC location in the best-track data. Defining large CS's as those with an effective radius greater than or equal to 500 km, we find that there are 128,460 observations of CS's, 113,768 observations of TC's, and only 17,303 matches. In other words, only 13% of the large CS's are tropical cyclones and only 15% of tropical cyclones are large CS. Therefore, the mesoscale systems studied by *Rossow and Pearl* [2007] were not, in general, tropical cyclones.

[4] In another study, *Cairo et al.* [2008] calculated the fraction of clouds in the tropical tropopause layer (TTL) that is attributable to tropical cyclones. Using TRMM's precipitation radar, they found the fraction to be about 3.5%. Comparing this to the similar fraction obtained by *Alcala and Dessler* [2002] for all tropical clouds, they concluded that TC's are not a preferred location for TTL-penetrating convection. An important caveat to this type of analysis is the fact that the precipitation radar detects more readily the larger hydrometeors found in continental convection as opposed to the finer droplets in marine clouds [*Zipser et al.*, 2006]. Thus, the TC fraction will be biased low. Moreover, it is altogether possible that TC deep convection penetrates the tropopause much more often than the tropical average even though it penetrates the base of the TTL at roughly the same rate as the tropical average. In order to explore this possibility, we will analyze convection at various different temperature thresholds.

[5] In this paper, we will quantify the fraction of tropical deep convection that occurs in tropical cyclones using 23 years of global infrared satellite imagery, global tropical-cyclone best-track data, and monthly reanalysis of tropopause temperature. Deep cloud will be disaggregated into TC and non-TC convection, as well as into a range of different temperature thresholds, to determine at what height, if any, TC clouds are dominant. Section 2 will discuss the data sets and the methods used to disaggregate clouds into TC and non-TC convection. Section 3 will present the results of the analysis and compare them to previous studies. Section 4 will conclude with a summary of the results, implications for the climate, and areas for improvement in future studies.

2. Methods

[6] We use 23 years (July 1983–June 2006) of infrared (IR) brightness temperatures from the DX data [*Rossow et al.*, 1996; *Rossow and Schiffer*, 1999] of the International Satellite Cloud Climatology Project (ISCCP) [*Schiffer and Rossow*, 1983]. This data set was chosen for its full

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coverage of the tropics and its large number of observations, which allow for the investigation of the tropical occurrences of relatively rare overshooting events. The DX data is generated by sub-sampling data from geostationary satellites (GOES, METEOSAT, etc.) and polar orbiters (NOAA AVHRR), which have native resolutions between 4 and 5 kilometers, down to observations spaced roughly every 30 kilometers. We have gridded this data at 0.1°, assigning each pixel the value of the smallest zenith-angle satellite observation within 50 km of it. Since this chain of processing – from 4–5 km to ~30 km to 0.1° – utilizes only sampling, the statistical distribution of IR temperatures in the gridded data is the same as in the original.

[7] One potential problem with using IR temperatures alone is that cirrus cloud might be included in our tally even though we are interested in deep convection. For temperature thresholds below about 245 K, thin cirrus should be excluded because their infrared brightness temperatures are warmer than their actual temperatures [*Machado et al.*, 1998]. Since the focus of this study is on clouds that penetrate the tropopause, the temperature thresholds of interest should be below the temperature where thin cirrus will pose a problem. On the other hand, restricting ourselves to very low temperatures reduces the sample size and increases the relative weight of spurious noise in the data. For example, if each temperature bin in the satellite data were to have the same additive noise, then bins with a low number of true counts would have a low signal-to-noise ratio. By examining spatial distributions of clouds below various temperature thresholds, it becomes clear that noise begins to contribute a significant number of spurious observations for thresholds at and below −15 K relative to the tropopause. For this reason, we do not present any data for thresholds below −15 K.

[8] The best track data was taken from the NCDC's three-hourly best-track data for all basins, which was produced by combining the JTWC and HURDAT databases and interpolating to every three hours (see ftp://eclipse.ncdc.noaa.gov/pub/hursat/b1/v03/global_tracks_3h.txt.gz). Due to the much-discussed deficiencies of these data (e.g., M. A. Lander, A comparison of typhoon best-track data in the western North Pacific: Irreconcilable differences, paper presented at the 28th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, 2008, Orlando, Florida), this data is difficult to use in ascertaining long-term trends of TC activity; for this reason, we do not attempt here to construct a time series of overshooting convection from tropical cyclones. The data is also inconsistent as to when storms are included and when they are excluded. Several of the storm tracks include storms during the point in their life cycles when they are only tropical depressions. Due to the large error bars inherent in the intensity values given in the best-track data, we make no effort to exclude storms during their tropical-depression stage.

[9] Overshooting cloud will be defined as cloud with an infrared brightness temperature (as determined by the satellite imagery) that is below the monthly averaged tropopause temperature at that location (as defined by NCEP reanalysis [*Kalnay et al.*, 1996]). All of the temperature thresholds discussed in this paper are understood to be relative to the local tropopause temperature; i.e., cloud that is below the −5 K threshold is understood to be at least 5 K colder than the local monthly averaged tropopause temperature. Clouds are considered to be associated with a tropical cyclone if they are within 1,000 kilometers (great-circle distance) of the center of a cyclone as defined by the best-track data. In this way, cloud-top temperature observations are grouped into TC and non-TC cloud. This procedure was checked by eye to confirm that a 1,000-km radius was large enough to encompass the tropical cyclones and small enough to exclude other nearby cloud systems. (For an animation of tropical brightness temperatures during 2005 with the 1,000-km circles, see www.romps.org/2009/overshoot.) All of the analyses in this study were also calculated using a 500-km radius, which gave virtually the same results.

[10] The use of monthly tropopause data means that we cannot account for variations of the tropopause temperature on sub-monthly timescales. Since both TC and non-TC convection can cool the local tropopause substantially, a cloud top temperature lower than the monthly mean tropopause temperature does not necessarily imply that convection has penetrated into the stratosphere. Instead, clouds may need to be 5 or 10 K colder than the monthly averaged tropopause to have actually penetrated the tropopause. The hope is that there is some temperature threshold for penetration that applies equally well to TC and non-TC clouds. In order for this to be the case, the magnitude and timescale of the tropopause lifting must be similar for both types. If the magnitude were different, then, obviously, the appropriate threshold would be different. If the timescales were different, then the tropopause cooling might average into the reanalysis temperature with different weights, thereby biasing the threshold.

[11] At the moment, there is no clear reason to expect a difference in either magnitude or timescale. Although TC's produce a local cooling of the cold-point tropopause by as much as about 10 K [*Koteswaram*, 1967; *Waco*, 1970], case studies [e.g., *Johnson and Kriete*, 1982] and statistical analysis of radiosonde data and satellite imagery [*Sherwood et al.*, 2003] show that tropical convection in general also leads to a cooling of the tropopause by as much as 5–10 K/day. The timescale of local tropopause cooling caused by a tropical cyclone is given by its linear size (on the order of 1,000 km) divided by its advection speed (on the order of 10 m/s), which gives a timescale on the order of a day. Similarly, 99% of all Convective Systems with penetrating convection have a duration of less than 100 hours, and 97% have a duration less than one day [*Rossow and Pearl*, 2007]. Therefore, tropopause cooling by either TC or non-TC clouds will be too short in duration to significantly affect the monthly reanalysis.

[12] Another possible concern is the use of satellite data with a native 4 or 5-km resolution. What is surprising is just how large a cloud top must be before it has better-than-even odds of being observed at its true temperature. In order for an observation to average over only the plume top, the center of the observation must not lie within a distance of $d/2$ from the edge of the plume, where d is the linear size of the observation pixel. Of all the observations that are randomly centered within a plume top of linear size D, only a fraction equal to $(D - d)^2/D^2$ will average over the plume top exclusively. In order for at least half of the observations

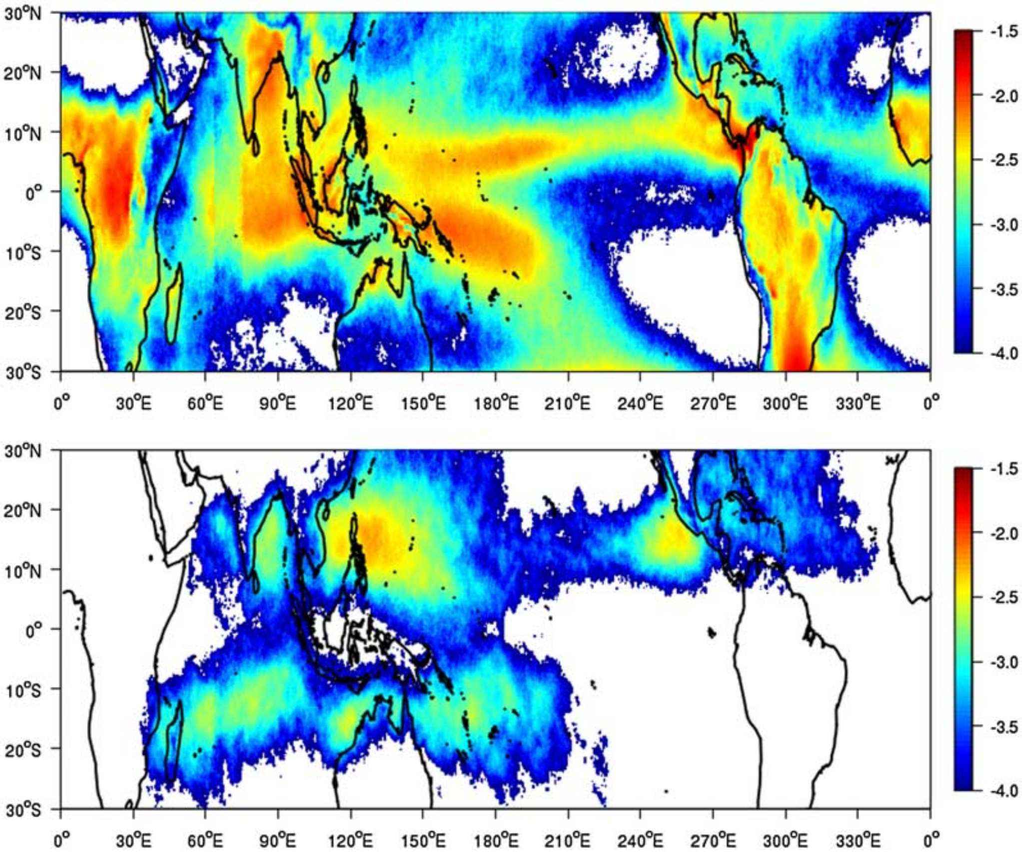

Figure 1. Base-ten logarithm of annually averaged probability of (top) overshooting non-TC cloud and (bottom) overshooting TC cloud.

to fall entirely within the plume top, the relationship between D and d must obey

$$D \geq \frac{\sqrt{2}}{\sqrt{2}-1} d \simeq 3.4d.$$

For a satellite resolution of 5 km, this is satisfied only for plumes of at least a 17-km diameter. This important point has been largely ignored in the literature: a 5-km-wide observation that is centered within a 17-km-wide cloud top has only a 50% chance of recording the true cloud-top temperature. Since most plumes are expected to be well below this size, any study using 5-km-resolution data will significantly underestimate the number of overshooting plumes. For relative frequencies of overshooting convection between TC and non-TC cloud systems, which is the main focus of this study, we need only that plume sizes be of the same horizontal size in these two categories.

3. Results

[13] The 23-year distribution of non-TC overshooting cloud is shown in the top panel of Figure 1. At each point on the map, the probability of overshooting cloud is given by the number of sub-tropopause-temperature observations divided by the total number of observations. Dividing by the total number of observations helps to remove the bias introduced by uneven satellite coverage. This map is qualitatively similar to maps generated with other thresholds and to previous maps in the literature that have used infrared temperatures to identify deep convection [*Hendon and Woodberry*, 1993; *Alcala and Dessler*, 2002; *Gettelman et al.*, 2002].

[14] The 23-year distribution of TC overshooting cloud is given in the bottom panel of Figure 1. This map shows overshooting TC cloud in the three belts of cyclone activity: the Northwest Pacific and North Indian Ocean, the Southwest Pacific and South Indian Ocean, and the Northeast Pacific and North Atlantic. The region with the highest probability of overshooting TC cloud is the region of the Northwest Pacific in the vicinity of the Philippines. The region with the second highest probability is in the Northeast Pacific, west of Mexico and Central America. Taking non-TC and TC cloud together, oceanic convection accounts for 60% of all overshooting cloud in the tropics. Since the oceans cover 73% of the tropics, we conclude that the majority of tropical overshooting clouds occurs over the ocean, but that the land has a higher density (events per time per area) of overshooting events, in agreement with previous work [*Rossow and Pearl*, 2007].

[15] Although most of the overshooting cloud in the tropics occurs outside of tropical cyclones, there are geographical regions where TC's do contribute the majority of the overshoots. Over large swaths of ocean between 10° and 30° latitude in both hemispheres, the fraction of overshooting cloud that is associated with tropical cyclones exceeds 50% by large margins. On average, tropical cyclones account for 33% of the overshooting cloud over the oceans

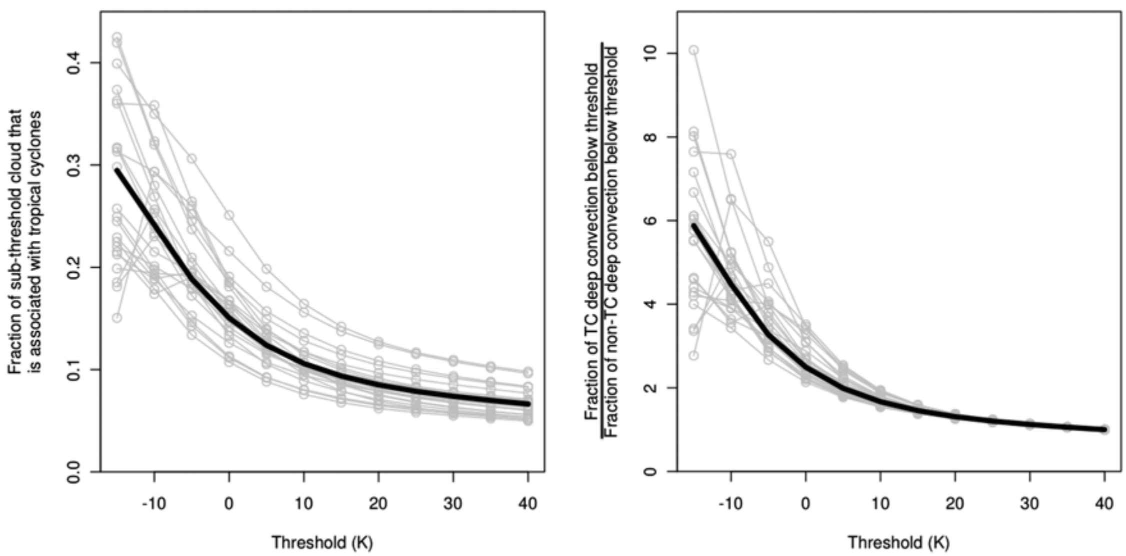

Figure 2. (left) Fraction of annually averaged sub-threshold cloud in the tropics (30°S to 30°N) that is associated with tropical cyclones. (right) Fraction of TC deep-convective cloud that is below the threshold divided by the fraction of non-TC deep-convective cloud that is below the threshold. Grey lines correspond to individual years, while the black lines give the mean.

between 15°N and 30°N in any given year. Over the ocean between 15°S and 30°S, tropical cyclones account for 22% of the overshoots. Over the entire tropics, defined as 30°S to 30°N, TC's account for 15% of all the overshooting cloud.

[16] In general, tropical cyclones account for a disproportionately large amount of very cold cloud. In other words, clouds within TC's contain a much higher fraction of very cold cloud than clouds outside TC's. This may be seen from the increasing fraction of tropical cold cloud that can be attributed to TC's as the threshold temperature is lowered, as shown in the left panel of Figure 2: the fraction of tropical cold cloud associated with TC's increases from 7% at a threshold of +40 K, to 15% at the tropopause temperature, to 29% at 15-K colder than the tropopause. Defining deep-convective cloud as cloud with a temperature within 40 K of the tropopause, 3% of non-TC deep convection overshoots the tropopause; this fraction is larger than the one percent obtained by *Rossow and Pearl* [2007] because they used a more generous definition of deep convection comprised of cloud below 245 K, which roughly corresponds to cloud within 55 K of the tropopause. In contrast to the 3% overshooting ratio for non-TC cloud, 8% of the deep convection in tropical cyclones penetrates the tropopause. At a threshold of 15 K below the tropopause temperature, these percentages become 0.05% and 0.30% for non-TC and TC cloud, respectively. That is, deep convection in tropical cyclones is six times more likely to overshoot the tropopause by 15 K as is deep convection elsewhere. To illustrate this point, the right panel of Figure 2 shows the relative frequencies with which TC and non-TC deep convection reach a cloud-top temperature less than a given threshold. By the definition of deep convection used here, the ratio is identically one at a threshold of 40 K.

4. Conclusions

[17] It appears that tropical cyclones contribute a disproportionately large amount of the convection that reaches the stratosphere. Although they account for only 7% of the deep convection in the tropics, they contribute 15% of the convection that overshoot the tropopause and at least 29% of the clouds that obtain temperatures 15 K below the temperature of the tropopause. It stands to reason, then, that TC's could play an important role in setting the mixing ratio of stratospheric water vapor. It is well known that increases in stratospheric water vapor lead to surface warming [*de F Forster and Shine*, 1999; *Shindell*, 2001]. It is also widely believed that global warming will lead to changes in the frequency and intensity of tropical cyclones [*Emanuel*, 1987, 2005; *Knutson et al.*, 2008]. Therefore, the results presented here establish the possibility for a feedback between tropical cyclones and global climate.

[18] At first glance, these results may appear to be at odds with that of *Cairo et al.* [2008], who found that the deep-convective clouds in TC's contain no higher fraction of TTL-penetrating cloud than deep-convective cloud outside TC's. But, compared to the cold-point tropopause (about 190 K), the base of the TTL lies at the relatively warm temperature of 210 K. From the second plot of Figure 2, it is clear that deep convection outside tropical cyclones penetrates the TTL (a threshold of roughly 20 K) almost as frequently as deep convection inside tropical cyclones, i.e., the ratio at a threshold of 20 K differs from one only slightly. It is only closer to the tropopause (a threshold of 0 K) that the disproportionate contribution from tropical cyclones becomes evident.

[19] The findings of this paper, however, are not without some complications of interpretation. There is the possibility that tropical cyclones lift and cool the tropopause more than other mesoscale systems; if true, then the higher frequency of cold cloud in tropical cyclones might not imply a higher rate of overshooting. Another concern is the effect of the relatively coarse 5-km resolution of the satellite imagery. If overshooting plumes in TC's are larger than the tropical average, then they will be more readily detected by coarse-resolution imagery, and this may explain

the higher observed fraction of deep convection that appears to overshoot in tropical cyclones. To assess whether this effect influences the results, future research will need to employ higher-resolution imagery.

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