CloudSat adding new insight into tropical penetrating convection
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1 Collocated observations of cloud-top height and cloud-profiling information from CloudSat and cloud-top temperature from MODIS are analyzed to determine where convective cloud top occurs in relation to the cold point tropopause and to characterize the internal vertical structure of these deep convective clouds. Three types of penetrating convection identified as cold-low (CL), cold-high (CH), and warm-high (WH) are defined according to the cloud-top temperature and height in comparison to the cold point tropopause height and temperature: It is suggested that CL, CH and WH types correspond to, respectively, the incipient, mature and dissipating stage of the convective lifecycle. Multiple lines of evidence, including characteristics of CloudSat radar profiles, test against the undiluted ascent hypothesis, and examination of convective system size, all lend support to this interpretation. Citation: Luo, Z., G. Y. Liu, and G. L. Stephens (2008), CloudSat adding new insight into tropical penetrating convection, Geophys. Res. Lett., 35, L19819, doi:10.1029/2008GL035330.

1. Introduction

2 Convection penetrating the tropical tropopause plays an important role in affecting the heat budget [Sherwood et al., 2003; Kuang and Bretherton, 2004] and moisture distributions [Danielsen, 1982; Sherwood and Dessler, 2000] within the tropical upper troposphere and lower stratosphere. Understanding these important influences requires, in part, ways of observing the tropics-wide distribution and frequency of deep penetrative convection and a number of ways to observe such convection from spaceborne platforms have been proposed. The most commonly used approach is to identify cold cloud tops using the IR brightness temperature in window channels with the ambient temperature of a reference level, usually the cold point tropopause [e.g., Gettelman et al., 2002; Rossow and Pearl, 2007]. Recently, the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR operating at a frequency of 13.8-GHz) was utilized to characterize the vertical structure and intensity of tropical penetrating convection [Liu and Zipser, 2005] and Liu et al. [2007] contrasted the PR observations with IR cloud top temperatures in an effort to understand the difference between IR- and PR-based convection climatologies.

[3] The launch of CloudSat in April 2006 [Stephens et al., 2008], which carries with it a 94-GHz cloud profiling radar (CPR) sensitive to both cloud- and precipitation-size particles, offers a new opportunity to study the properties of convection and perhaps offers a new dimension to our understanding of the tropical overshooting convection. Chung et al. [2008] used CloudSat data and collocated IR information (from Meteosat-8) to relate warmer water vapor pixels to high-reaching tropical deep convection, a concept that was originally proposed by Schmetz et al. [1997]. It was found that satellite pixels whose brightness temperature (TB) in the water vapor absorption band (≈6.3 μm) is higher than that in the window channel (≈11 μm) are usually associated with clouds with tops above 14 km [Chung et al., 2008].

[4] In this paper, we analyze CloudSat and MODIS (Moderate-Resolution Imaging Spectroradiometer onboard Aqua satellite, which flies in formation with CloudSat, being separated by only ~2 minutes) data to gain further insight into tropical penetrating convection. Specifically, we use these collocated observations to investigate the heights of cold convective cloud tops in relation to the tropopause. The existence of satellite pixels with IR brightness temperatures colder than the corresponding local tropopause does not necessarily mean that convection has penetrated into the lower stratosphere because air parcels inside convective core typically follow a different thermodynamic path (i.e., moist adiabatic) than the environment. For example, while the lapse rate of the environment is very small (close to isothermal) from 14 km to the cold point tropopause (~17 km), rising air parcels within clouds will continue to follow adiabatic lapse rate (which is about 10 K/km at these altitudes where latent heating is negligible). With simultaneous, independent measurements of cloud-top height (CloudSat) and cloud-top temperature (MODIS), penetrating convection can be further divided into several categories, each of which has its own unique characteristics that reveal the evolution history of itself. Section 2 describes analysis concept and data used. Results and interpretations are presented in Section 3. Section 4 discusses open questions raised by this study and section 5 summarizes the study.

2. Analysis Concept and Data

[5] Suppose an undiluted convective updraft overshoots the level of neutral buoyancy and continues to rise adiabatically. The cloud top becomes increasingly colder than the surrounding air due to the smaller lapse rate of the environment near the tropopause region (assuming mixing is insignificant). Thus it is possible that the temperature of the convective tower is colder than that of the cold point tropopause (CPT) before it reaches the height of the tropopause. We call this type of penetrating convection “cold-low” or CL type. On the other hand, if a convective turret penetrates through the CPT and starts to detrain, it will
Examples of (left) CL, (middle) CH, and (right) WH type tropical penetrating convection. The filled arrows show where the penetration occurs. The color scale is for radar reflectivity in dBZ.

mix with the warm environment of the lower stratosphere and consequently the cloud top temperature may be warmer than the CPT. Alternatively, it is also possible that as large particles fall to lower levels, the upper portions of these deep clouds might contain mostly small ice crystals and the emission now arises from deeper within the cloud making the cloud appear warmer in the IR brightness temperature compared to the CPT. Either case, we call this “warm-high” or WH type. The CL scenario corresponds to the incipient or growing stage of an overshooting event with little dilution, whereas the WH type is associated with the dissipating stage. There is, of course, a third type of penetrating convection that is both colder and higher than the local CPT, which we call “cold-high” or CH type. It is most likely related to newly penetrated convective turret with moderate level of mixing with the environment.

Measurement of cloud-top temperature (CTT) alone as provided by IR sensors, however, is not sufficient to differentiate these scenarios. We need simultaneous, independent measurements of cloud-top height (CTH) and preferably some idea of the structure below the cloud top. CloudSat provides this important information (synergistic value of collocated CTT and CTH measurements can also be found in a recent study of hurricanes using CloudSat and MODIS by Luo et al. [2008]). Moreover, cloud-profiling capability of the 94-GHz CPR offers a glimpse into the internal vertical structures of penetrating convection. It has been suggested whether penetrating convection hydrates or dehydrates the tropical tropopause region depends on the size of the ice crystals lofted [e.g., Jensen et al., 2007]. CloudSat offers some insight into the microphysical aspect of these deep convective clouds to help answer this question. Figure 1 shows a typical example of each of the three types of penetrating convection.

Specifications concerning CloudSat data are given by Stephens et al. [2008] and the CloudSat Data Processing Center at http://cloudsat.cira.colostate.edu. Here, we provide a few essential facts. The primary instrument on CloudSat is a 94-GHz, nadir-pointing, cloud profiling radar. The CloudSat data footprint is approximately 1.7 km along track and 1.3 km across track. The effective vertical resolution is 480 m, with oversampling at 240-m resolution. Several CloudSat products are used in this study. They include: 1) 2B-GEOPROF [Mace et al., 2007], which provides cloud mask and radar reflectivity. Cloud mask value ≥30 is used to identify clouds and to locate cloud tops. 2) MODIS-AUX giving the collocated MODIS radiances. The collocation is made through 3 × 5 grids of 1-km MODIS data centered on each CloudSat profile location. To minimize random noise, radiances from all 15 grids are averaged to match the CloudSat profile. 3) 2B-CLDCLASS, which classifies CloudSat profiles into eight basic cloud types consistent with World Meteorological Organization (WMO) standard [Sassen and Wang, 2008]. One cloud type of particular importance to this study is deep convection, which extends from the surface to the upper troposphere and shows high precipitation intensity. To avoid contamination from other non-convective forms of high-level clouds, our analysis is limited to the deep convective type only. 4) ECMWF-AUX containing temperature and moisture profiles from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis interpolated in time and space to the CloudSat track. 5) 2B-GEOPROF-LIDAR that combines CloudSat CPR and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) lidar cloud masks. A whole year (2007) of CloudSat data are analyzed over 15S-15N. The reason for choosing 15S-15N is that cold point tropopause is easily identifiable within this latitude range as a sharp turning point in temperature profiles.

3. Results and Interpretations

We first present the following four observational facts before attempting any interpretation (and speculation): 1) distribution of different types of penetrating convection, 2) characteristic internal vertical structure, 3) test against undiluted adiabatic ascent, and 4) nature of the convective systems that produce the penetrating motions.

3.1. Observations

3.1.1. Distribution of Different Types of Penetrating Convection

Previous studies have shown that only a small fraction of tropical clouds penetrate to the altitude of the tropopause [e.g., Gettelman et al., 2002; Liu and Zipser, 2005; Rossow and Pearl, 2007]. Between 15S and 15N averaged over a whole year, the occurrence frequency for deep convection (DC) according to the 2B-CLDCLASS algorithm is approximately 3.9%; the number is slightly larger over land (4.6%) than over ocean (3.7%). Out of this small pool of deep convection profiles, only ~1.0% (i.e., 1.0% of the DC) have cloud tops colder than the CPT (the sum of CL and CH in Table 1). This occurrence broadly agrees with the statistics as given by Rossow and Pearl [2007], despite different definitions of deep convection. CloudSat data also show that approximately 1.3% of the DC penetrates beyond the altitude of the CPT. However, the occurrence of cold cloud does not uniquely establish the
occurrence of high-reaching convective clouds, and in order to determine the penetrative convection, we break them down into three types: CL, CH and WH. Table 1 lists the occurrence frequencies of these type: WH type is the most abundant among the three (0.89% of DC), followed by CL type (0.60% of DC), while CH is the least (0.40% of DC). Separated over land and ocean, CL and CH type are a little more than twice as frequently observed over land than over ocean. WH type, on the other hand, is slightly more frequent over ocean.

3.1.2. Characteristic Internal Vertical Structure

[10] The differences between the CL, CH and WH categories are further elucidated in the CloudSat CPR profiles. Recent studies of millimeter wavelength cloud radars have established that reflectivities of 0 dBZ and 10 dBZ are effective proxies for tracing the precipitation-sized particles within convective clouds [Stephens and Wood, 2007; Haynes and Stephens, 2007; J. M. Haynes et al., Rainfall retrieval over the ocean with spaceborne W-band radar, submitted to Journal of Geophysical Research, 2008]. Following these studies, we calculate the echo top height (ETH) for 0 dBZ and 10 dBZ to determine to what extent large size particles are lofted by different types of penetrating convection. Table 2 summarizes the statistics of ETH(0 dBZ), ETH(10 dBZ), CTH (which roughly corresponds to the ETH of -28 dBZ), and the distance between the CTH and ETH. Clearly, convective cores for the CL and CH types reach to higher altitudes than do the convective cores in the WH clouds. The contrast is especially striking between CL and WH: despite the fact that WH type convection as a whole rises higher than CL, the corresponding precipitation ETH is noticeably lower. Collocated CALIPSO lidar data, which is included in the CloudSat 2B-GEOPROF-LIDAR product, were also briefly analyzed for comparison. Because CALIPSO lidar is sensitive to very small particles that are not detected by CloudSat, CTH as defined by CALIPSO is almost always higher than that by CloudSat. Table 2 shows that CTH from CALIPSO is generally within ~300 m of that from CloudSat, confirming clouds analyzed here are indeed deep, optically thick convective clouds. Figure 2 schematically summarizes the characteristics of different types of penetrating convection.

Table 1. Occurrence Frequencies for Different Types of Penetrating Convection out of the Deep Convection\(^a\)

<table>
<thead>
<tr>
<th>Type</th>
<th>All</th>
<th>Land</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL fraction (out of DC)</td>
<td>0.60%</td>
<td>0.98%</td>
<td>0.41%</td>
</tr>
<tr>
<td>CH fraction (out of DC)</td>
<td>0.40%</td>
<td>0.71%</td>
<td>0.31%</td>
</tr>
<tr>
<td>WH fraction (out of DC)</td>
<td>0.89%</td>
<td>0.71%</td>
<td>0.93%</td>
</tr>
</tbody>
</table>

\(^a\)CL, CH, and WH, different types of penetrating convection; DC, deep convection. The occurrence frequency 0.60% for CL, for example, refers to 0.60% of the DC.

3.1.3. Undiluted, Adiabatic Ascent

[11] Independent measurements of CTT and CTH provide a direct check on how much dilution convective towers experience. This is accomplished through a comparison of the CTT with the temperature deduced assuming adiabatic, undiluted ascent from the planetary boundary level to the altitude of cloud top (referred to as T-adiabatic). ECMWF equivalent potential temperature (\(\theta_e\)) at 925 or 1000 hPa, whichever is greater, is used to calculate T-adiabatic, following the procedure of Liu and Zipser [2005]. Our calculation shows that the differences between CTT and T-adiabatic, when averaged over a whole year of data, are 1.0 K, 7.7 K and 14 K for CL, CH, and WH types, respectively. Thus we infer that the CL type comes closest to undiluted adiabatic ascent, whereas CH experiences some moderate level of mixing (with the environment), and WH suffers the most dilution. (Caution, however, should be taken in interpreting the absolute values of the differences between CTT and T-adiabatic because of potentially limited cloud opacity near cloud top. This issue will be discussed in more details in Section 4.)

3.1.4. Nature of the Convective Systems that Produce the Penetrating Motions

[12] The “snapshot” nature of A-Train measurements does not present the whole history of the convective systems that produce the penetrating motions. To obtain this information, we need observations from geostationary satellites that track the evolution of each convective system throughout its lifecycle. The ISCCP (International Satellite Cloud Climatology Project) convection tracking or CT database as used by Rossow and Pearl [2007] is an ideal information source for this purpose. However, the ISCCP CT database has not yet been extended to cover the CloudSat period (although it is under plan for the near future (W. Rossow, private communication, 2008)). Lacking such data, we examined the characteristics of the penetrat-

Table 2. Statistics for the Internal Vertical Structure of Different Types of Penetrating Convection\(^a\)

<table>
<thead>
<tr>
<th>Type</th>
<th>CTH (CloudSat)</th>
<th>CTH (CALIPSO)</th>
<th>Height (0 dBZ)</th>
<th>Distance (CTH-CloudSat to 0 dBZ)</th>
<th>Height (10 dBZ)</th>
<th>Distance (CTH-CloudSat to 10 dBZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>15,752</td>
<td>16,119</td>
<td>14,247</td>
<td>1,505</td>
<td>11,629</td>
<td>4,123</td>
</tr>
<tr>
<td>CH</td>
<td>16,686</td>
<td>16,894</td>
<td>15,026</td>
<td>1,642</td>
<td>11,948</td>
<td>4,719</td>
</tr>
<tr>
<td>WH</td>
<td>16,521</td>
<td>16,750</td>
<td>14,035</td>
<td>2,486</td>
<td>10,769</td>
<td>5,752</td>
</tr>
</tbody>
</table>

\(^a\)The unit is meter.
ing convective systems by analysis of the structure along the CloudSat track in granules that contain penetrating convection. Although somewhat subjective, our analysis suggests that the CL type is usually associated with isolated convective cloud. Convective updrafts are strong as inferred by high altitudes reached by parcels of the large radar echo. The relatively small horizontal span of CL convection also suggests this convection is occurring in the early stages of the lifecycle. 2) CH type convection is associated with cloud top brightness temperature could be attributed to mixing with the warmer environment warming cloud top, or the lower level of emission occurring deeper into the cloud or both.

4. Discussions

[14] Although CloudSat offers new insight into the character of tropical penetrative convection, there is a limitation to the study that warrants mention. The approximate 1:30 am/pm equatorial crossing time of the A-Train constellation means that important phases of the diurnal cycle of the tropical deep convection are not sampled. This issue is more serious over land than over ocean as continental deep convection has a distinctively pronounced peak during late afternoon [e.g., Soden, 2000; Liu and Zipser, 2005]. Moreover, different stages of convection also experience different diurnal phases [Machado et al., 1998]. Therefore, the statistics of occurrence frequencies provided in Table 1 should be considered tentative and is expected to be altered when sampling whole diurnal cycle (although Table 1 shows that stronger convection already starts to favor land over ocean in early afternoon).

[15] Another potential caveat lies in the use of IR TB to designate CTT. Depending on the “fuzziness” near the cloud top, the hydrometeor cloud top (as measured by cloud radar or lidar) in general will occur at higher levels than the cloud top inferred from IR radiometry. Sherwood et al. [2004] and Minnis et al. [2008] have shown that lidar-derived CTH is about 1–2 km higher than that from IR TB for the thicker, cold clouds, presumably in connection with deep convection. CPR-derived CTH is lower than that from lidar, but the difference is very small (~300 m) for the three convective cloud types identified in this study (which correspond mostly to convective cores). Hence, we expect that the temperature difference between TB and T-adiabatic as calculated in the previous section may partly come from limited and variable cloud opacities. The WH type is affected most because of smaller ice particles and/or lower ice water content (IWC) near the cloud top implying a smaller IR emissivity and emission from deeper within the cloud. However, this is still consistent with our interpretation of the WH type convection because at the dissipating stage of convective lifecycle, larger particles have already sunk to lower levels. CL type should suffer minimal impact of limited cloud top opacity because of larger ice particles and/or higher IWC near the cloud top. The small mean difference between TB and T-adiabatic (i.e., 1.0 K) also seems to support this conclusion.

5. Conclusions

[16] One year of CloudSat and MODIS data are analyzed in an effort to add new insight into our understanding of tropical penetrating convection. Emphasis is placed upon exploiting new observations from CloudSat (i.e., cloud-top height and cloud profiling information), in conjunction with traditional means of observing penetrating convection with IR radiometry to determine where cold convective cloud top occurs in relation to the cold point tropopause and to characterize the internal vertical structure of these convective clouds. Based on the cloud-top temperature and height of the convection, three types of penetrating convection are identified when this information is compared with the tropopause heights and temperatures - cold-low (CL), warm-high (WH) and cold-high (CH). The following characteristics of these three types of convection are observed:

[17] 1. Convective strength: CL and CH convection contain more intense cores than is observed for WH convection as implied by the much higher echo top heights of large reflectivities of CL and CH convection. CL and CH are also more prevalent over land while WH is slightly more prevalent over ocean.

[18] 2. Undiluted, adiabatic ascent: CL convection appears to be represented most closely by undiluted, adiabatic ascent from the planetary boundary level. CH convection shows some dilution by mixing and WH convection undergoes most mixing or the greatest dilution among the three convective types.

[19] 3. Nature of convective systems: CL convection usually occurs as isolated convection tens of km in size; CH and WH convection, on the other hand, are embedded within larger MCSs.

[20] Based on these observations, we suggest that CL is associated with the incipient stage of penetrating convection, CH with the mature stage, and WH is representative of the “aged” or dissipating penetrative convection. These interpretations will be further tested when the ISCCP CT database, which contains the whole history of each convective system, becomes available.

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the paper, especially the interpretation of different types of penetrating convection.

References


