Terminal Vs Transient Cumulus Congestus: A CloudSat Perspective

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Abstract

While cumulus congestus as an important mode of tropical convection has been established, many of the previous studies that rely on radar observations usually capture them as snapshots. A logical question to consider is: are the statistics gathered from snapshot observations of cumulus congestus really reflective of this mode of convection that ceases its growth at these intermediate levels (terminal cumulus congestus), or will the convection being observed continue to ascend to greater altitudes to become deep

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convection at a later time (transient cumulus congestus)? This short article strives to answer this question by analyzing simultaneous, independent measurements of CTH and CTT from CloudSat and MODIS, together with CloudSat radar profile and collocated ECMWF analysis. It is found, based on analysis of one year of data, that ~42% of the oceanic and ~36% of the continental cumulus congestus observed by the snapshot views are in transient mode that will ascend to greater altitude at a later time. The analysis concept used in this study, which gives “static” snapshot observations some “dynamic” context, can be applied to analyze convection of all types.

1. Introduction

Tropical convection has historically been thought of as primarily consisting of two modes: shallow convection such as trade wind cumulus with tops near 2-4 km and deep convection having towering tops higher than 12 km (Malkus and Riehl 1964). Johnson et al. (1999) analyzed shipboard precipitation radar data from Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) and other field campaigns and suggested that there is a third mode, namely, cumulus congestus that tops out at around the melting level, establishing the concept of trimodal distribution of tropical convective clouds. Stephens and Wood (2007) analyzed ground-based and aircraft-based millimeter-wave cloud radar from multiple sources and confirmed the finding of Johnson et al. (1999). Moreover, it was found that much of the tropical precipitation comes from multilayered clouds with the predominant mode being cirrus overlying cumulus congestus (Stephens and Wood 2007). More recently, data from the CloudSat mission (Stephens et al. 2008) further confirms the trimodality of
tropical convection and extends the survey to the whole tropics (Haynes and Stephens 2007).

While cumulus congestus as an important mode of tropical convection and thus a unique diabatic heat source has been established, many of the previous studies that rely on radar observations usually capture them as snapshots (e.g., nadir pointing cloud radar from Atmospheric Radiation Measurements sites or from CloudSat). Very few studies really sample the whole lifecycle of individual convective clouds (with the notable exception of Houze and Cheng 1977, who used precipitation radar and Machado et al. 1998, who analyzed geostationary data). A logical question to pose is: are the statistics gathered from snapshot observations of cumulus congestus really reflective of this mode of convection that ceases its growth at these intermediate levels or will the convection being observed continue to ascend to greater altitudes and thus become deep convection at a later time? Unless we track their whole lifecycle, we cannot differentiate between these two scenarios using only radar snapshot images. The motivation for this study is thus to seek an answer to this question: how many cumulus congestus clouds captured by cloud radar as snapshots have already lost buoyancy and ceased growth (which we call *terminal* cumulus congestus) and how many will continue to rise (which we call *transient* cumulus congestus)? Strictly speaking, *transient* cumulus congestus as defined this way may not be cumulus congestus but most likely deep convection in its early stage. However, we adopt this terminology to be consistent with past studies of cumulus congestus (e.g., Jensen and Del Genio 2006, Stephens and Wood 2007, Haynes and Stephens 2007). The newly launched CloudSat (which carries with it a 94-GHz cloud profiling radar), together with other members of the A-Train constellation (Stephens et al.
2002), will be used in this study to explore this question. Section 2 presents the analysis concept and data used. Results are shown in Section 3. Section 4 discusses the implication of the study and open questions. Section 5 summarizes the study.

2. Analysis Concept and Data

If our observations of convection only consisted of IR imagery from satellite plus local sounding information, we would not have been able to tell if a convective cloud will continue to rise or has already lost buoyancy. IR Brightness temperature (TB) alone gives the cloud-top temperature (CTT) at best assuming clouds are blackbody, but without knowing independently the cloud-top height (CTH), we cannot make use of the sounding data to decide if the CTT is warmer or colder than the ambient temperature of the same height level. No inference can thus be made about the buoyancy of the convective cloud top. Actually, most IR-based retrievals of CTH assume that CTT equals the ambient temperature so that CTH can be deduced by finding from the sounding data the height level whose temperature is equal to the TB. To determine if a cumulus congestus cloud is *terminal* or *transient*, we need independent, simultaneous observations of CTH and CTT, as well as sounding information. CloudSat and MODIS (onboard Aqua), which fly in formation with each other being separated by only ~ 2 min, make an ideal tool for tackling this problem. Furthermore, the cloud-profiling capability of the CloudSat 94-GHz cloud profiling radar (CPR) offers a glimpse into the internal vertical structure of convection and will help identify the convective cores for analysis. Two recent publications by Luo et al. (2008a, 2008b) give examples how CloudSat and
MODIS can be used synergistically for understanding tropical deep convection and hurricanes.

Figure 1 is a thermodynamic schematic of how terminal and transient cumulus congestus clouds differ in terms of equivalent potential temperature ($\theta_e$). If a convective updraft is totally undiluted during ascent, it will follow the thermodynamic path A to B then to C, conserving $\theta_e$. Now, if the CloudSat radar (or any other cloud radar) happens to capture it at the developmental stage corresponding to B, without further investigation one may interpret it as cumulus congestus. But if CTT at B is known and compared with the ambient temperature, one will find that CTT for this cloud at B is much warmer than the ambient temperature, suggesting cloud top is still positively buoyant and will continue to ascend to the corresponding level of neutral buoyancy (LNB) and may even overshoot that level (see Luo et al. 2008b for CloudSat depictions of various types of overshooting convection). On the other hand, if a convective updraft is accompanied by significant amount of entrainment of cold and dry ambient air on ascent, it may find itself settling at B, where CTT is equal to the ambient temperature. Convection then ceases to grow, making it a terminal cumulus congestus. In between these two extremes (AB and AB), there could always exist a middle ground in which entrainment is not as severe as the AB case such that the convective turret follows the path AB. AB is also a transient cumulus congestus in the sense that convection will continue to grow (although not to the undiluted LNB). In the next section, we will describe how we use CloudSat, MODIS and ancillary data to sort out terminal and transient cumulus congestus.

Data used in this study are mostly from the CloudSat mission (Stephens et al. 2008). The primary instrument on CloudSat is a 94-GHz, nadir-point, cloud profiling radar with
footprint of approximately 1.7 km along track and 1.3 km across track; the effective vertical resolution is 480 m oversampled to 240 m. The CloudSat products used are as follows (they are identical to those used in Luo et al. 2008b and are available to the public via the CloudSat Data Processing Center at http://cloudsat.cira.colostate.edu): 1) CloudSat 2B-GEOPROF containing cloud mask and radar reflectivity, 2) MODIS-AUX having collocated 3 × 5 grids of 1-km MODIS brightness temperatures centered on each CloudSat profile location, 3) 2B-CLDCLASS to identify convective cloud types, 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. Readers who are interested in knowing these CloudSat products in more detail are referred to Luo et al. (2008b) and references therein. A whole year of data (2007) is analyzed over 15S-15N.

3. Results

We first select cumulus congestus cases from CloudSat radar profiles. The criteria are as follows: 1) CTH derived from CloudSat is located in between 3 and 9 km, following Jensen and Del Genio (2006); 2) CPR shows continuous radar echo from cloud top to the ground, excluding non-convective, layered cloud types; 3) 10 dBZ echo top height (ETH) is within 2 km of the CTH-CloudSat, 0 dBZ ETH within 1 km of the CTH-CloudSat, and CTH-CALIPSO within 1 km of CTH-CloudSat. These are the characteristics of active convective core as observed in Luo et al. (2008b). In addition to
all these, we also require that the $3 \times 5$ grids of 1-km MODIS brightness temperatures are uniform enough (standard deviation less than 3 K) so that averaged TB across the $3 \times 5$ grids does not sample any lower clouds or the warm surface. This is a necessary step because many of the cumulus congestus cases that pass conditions 1 through 3 are small in size so that TB varies substantially within short distances, making it difficult to find a representative CTT to compare with the ambient temperature. Figure 1 gives an example of cumulus congestus selected according to these criteria.

Once cumulus congestus clouds are selected from CloudSat profiles, it is straightforward to evaluate their cloud top buoyancy: we simply compare CTT with the ambient temperature of the same height level ($T_{env}$), which is derived from CTH and ECMWF analysis. It is worth stressing again that simultaneous, independent measurements of CTT and CTH are critical to the calculation of $T_{env}$ and thus the evaluation of the cloud top buoyancy. Calculated over the tropical oceanic area, 83% of the cumulus congestus so selected show $CTT - T_{env}$ greater than 0, suggesting their cloud tops are positively buoyant. However, IR TB does not correspond precisely to the physical CTT because of limited emissivity near cloud top. TB measures the “radiometric” cloud top, which occurs at optical thickness of one from the physical cloud top. This measure of cloud top is almost always lower and warmer than that by cloud radar and lidar (Sherwood et al. 2004, Minnis et al. 2008). The magnitude of the difference depends on the “fuzziness” of cloud top. Sherwood et al. (2004) and Minnis et al. (2008) showed that for deep convection, this difference is about 1 km, which approximately correspond to the optical thickness of one, given that cloud-top ice water content (IWC) is $\sim 0.015$ g/m$^3$. For cumulus congestus clouds that are selected through
the aforementioned strict criteria and whose cloud tops are made of water or mixed-phase, the cloud water content (CWC) near cloud top is probably greater than that of the ice-topped deep convection. Hence, the difference between IR and radar/lidar CTHs should be around or even smaller 1 km. Considering the lapse rate within convective clouds roughly follows the moist adiabat, this height difference will translate to a difference between TB and CTT of roughly 5 – 7 K for the height range of 3 – 9 km.

Figure 2 shows the histogram of CTT minus $T_{env}$ when a 6 K adjustment is applied to the TBs. After this adjustment, the percentage of transient cumulus congestus becomes 42%.

There are land-ocean differences in the percentage of transient cumulus congestus: when the same procedure is run through data over tropical land areas, the percentage is 36%. One might expect a larger fraction of continental cumulus congestus captured in snapshots are deep convection in the growing stage. Lack of such a trend may be related to the limited sampling of diurnal cycle by CloudSat (~ 1:30 am/pm). A follow-up study is being conducted, using Atmospheric Radiation Measurement (ARM) data that capture the complete diurnal cycle at a few tropical locations (Manus, Naru, and Darwin), to understand the impact of convective diurnal cycle on the percentage of transient cumulus congestus.

4. Discussion

The motivation for this study is that many of the previous (and current) observations of cumulus congestus that rely on cloud radar observations usually capture convective clouds as a snapshot, the interpretations of which must be viewed with caution. Luo et
al. (2008b) showed that with careful analysis of simultaneous CTT, CTH, cloud profiling information and collocated sounding data, snapshots can be used to infer different evolitional stages of tropical deep convection. In this study we follow similar procedures to separate cumulus congestus that have lost buoyancy (*terminal*) from those that will continue to ascend (*transient*). *Thus the essence of the study is to give the “static” snapshots of convection a more “dynamic” context.* The same method can be applied to analyze all convection including shallow and deep convection (which is our ongoing research). We single out cumulus congestus in this short article to demonstrate the method and concept that will eventually lead to a more complete survey of all convective clouds.

In the meantime, there are a few limitations that are worth mentioning. First, the percentage of *transient* cumulus congestus as inferred from this paper, namely, 42% over tropical ocean and 36% over tropical land, should be considered tentative. A number of factors can contribute to uncertainty in this estimate: 1) the approximate 1:30 am/pm equatorial crossing time of the A-Train constellation may not catch the full diurnal cycle of cumulus congestus; 2) the difference between IR TB and CTT is not directly measured for each case (for example, for 5 K and 7 K adjustments, the percentage for oceanic *transient* cumulus congestus will become, respectively, 56% and 31%); 3) there are uncertainties in the collocated ECMWF temperature/moisture profiles. Also, we only selected cumulus congestus cases that have homogeneous cloud top within a few km; some small cumulus congestus may have very “rough” tops and are not included in this analysis. Rossow and Pearl (2007) showed that in general smaller deep convective systems tend to penetrate lower. If this trend holds for cumulus congestus, our statistics
on transient cumulus congestus may be an underestimate when very small convective systems are excluded. Nevertheless, we believe it is a robust result that a significant fraction of the cumulus congestus clouds captured by cloud radars as snapshots are on their way to greater altitude, or in the terminology of this paper, transient cumulus congestus. Second, it remains a question as to how much higher these transient cumulus congestus reach after the snapshots are caught by CloudSat. Some of them, with temperature surplus of only a few degrees, may not ascend much higher and thus will still be classed as cumulus congestus even if their whole lifecycles are sampled. Others with large temperature surplus may become deep convection at a later time. It is our ongoing research to run the same analysis through all convective clouds in CloudSat database to investigate the eventual “fate” of these transient cumulus congestus.

5. Conclusions

This short article strives to answer the question how many cumulus congestus that are captured by cloud radar as snapshots have already lost buoyancy (terminal cumulus congestus) and how many will continue to ascend (transient cumulus congestus). This is an important question because most of the cloud radar observations see convection as snapshots and statistical inferences about these clouds are likely to be biased by analysis of these snapshots. We address this question by analyzing simultaneous, independent measurements of CTH and CTT from CloudSat and MODIS, together with CloudSat radar profile and collocated ECMWF analysis. It is found, based on analysis of one year of CloudSat data, that ~ 42% of the oceanic and ~ 36% of the continental cumulus congestus observed by the snapshot views are in transient mode that will ascend to
greater altitude at a later time. Although these numbers should be treated as tentative, we believe it is a robust result that a significant fraction of apparent cumulus congestus as captured by cloud radars as instantaneous snapshots have not lost buoyancy. The analysis concept used in this study, which gives “static” snapshot observations some “dynamic” context, can be applied to analyze convection of all types. This is our ongoing work.

Acknowledgments

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References:


Figure/Table Captions

Figure 1. (Left) Schematics showing the thermodynamic paths of terminal Vs transient cumulus congestus. The solid and dashed curves refer to, respectively, equivalent potential temperature ($\theta_e$) and saturation equivalent potential temperature ($\theta_e^*$) of the ambient air. Path AB1 is that of a terminal cumulus congestus. Path AB2 is that of an undiluted deep convection that will at a later time ascend to the LNB at C. Path AB3 is a scenario in between the two extremes. Both AB2 and AB3 are examples of transient cumulus congestus. (Right) A typical example of cumulus congestus cloud observed by CloudSat that is selected according to the criteria as explained in the text of Section 3.

Figure 2. Histogram of CTT minus $T_{env}$ under the assumption IR TB is on average 6 K warmer than CTT. Only results over ocean are shown.
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