When, Where and to What Extent Do Temperature Perturbations near Tropical Deep Convection Follow Convective Quasi Equilibrium?

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Abstract

Convective Quasi-Equilibrium (CQE) is often adopted as a useful closure assumption to summarize the effects of unresolved convection on large-scale thermodynamics, while existing efforts to observationally validate CQE largely rely on specific spatial domains or sites rather than the source of CQE constraints—deep convection. This study employs a Lagrangian framework to investigate leading temperature perturbation patterns near deep convection, of which the centers are located by use of an ensemble of satellite measurements. Temperature perturbations near deep convection with high peak precipitation are rapidly adjusted towards the CQE structure within the two hours centered on peak precipitation. The top 1% precipitating deep convection constrains the neighboring free-tropospheric leading perturbations up to 8 degrees. Notable CQE validity beyond a 1-degree radius is observed when peak precipitation exceeds the 95th percentile. These findings suggest that only a small fraction of deep convection with extreme precipitation shapes tropical free-tropospheric temperature patterns dominantly.

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Key Points:

- Tropical temperature perturbations near extreme deep convection rapidly conform to convective quasi equilibrium in a two-hour window.
- Only the top 5% precipitating deep convection can modulate hourly tropical temperature patterns beyond a 1-degree radius.
- Top 1% precipitating deep convection constrains nearby temperature perturbations up to an 8-degree radius during peak precipitation.

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Abstract

Convective Quasi-Equilibrium (CQE) is often adopted as a useful closure assumption to summarize the effects of unresolved convection on large-scale thermodynamics, while existing efforts to observationally validate CQE largely rely on specific spatial domains or sites rather than the source of CQE constraints—deep convection. This study employs a Lagrangian framework to investigate leading temperature perturbation patterns near deep convection, of which the centers are located by use of an ensemble of satellite measurements. Temperature perturbations near deep convection with high peak precipitation are rapidly adjusted towards the CQE structure within the two hours centered on peak precipitation. The top 1% precipitating deep convection constrains the neighboring free-tropospheric leading perturbations up to 8 degrees. Notable CQE validity beyond a 1-degree radius is observed when peak precipitation exceeds the 95th percentile. These findings suggest that only a small fraction of deep convection with extreme precipitation shapes tropical free-tropospheric temperature patterns dominantly.

Plain language summary

Convective Quasi-Equilibrium (CQE) is a concept in atmospheric science that explains a state where the influence of deep convection (cumulonimbus clouds) and large-scale atmospheric forces is balanced, causing certain thermodynamic properties close to specific reference profiles. Previous studies have focused on how temperature changes relate to the CQE structure but in specific regions or sites while this study aims areas near deep convection—supposedly the source of CQE constraints. Using a unique framework with data from multiple satellites, we tracked the evolution of temperature patterns near deep convection. We found that temperatures near deep convection with extreme rainfall are adjusted towards the CQE structure rapidly within

2 hours of maximum rainfall. However, only the deep convection with top 5% extreme rainfall can effectively affect nearby temperature pattern beyond 1 degree, with the top 1% influencing up to an 8-degree radius. These findings highlight the dominant impact of a small fraction of deep convection, particularly those with extreme rainfall, on nearby temperature patterns.

1. Introduction

The Convective Quasi-Equilibrium (CQE) theory, first introduced by Arakawa & Schubert (1974) , posits that convective energy within cumulus ensemble remains in statistical equilibrium, balanced between large-scale replenishment and cloud-scale consumption. Intrinsic to the equilibrium, moist convection actively steers vertical temperature perturbations towards specific reference profiles, a principle embedded in various moist convective adjustments (Ahmed et al., 2020; Betts, 1973; Betts & Miller, 1986; Kuo, 1974; Manabe et al., 1965) and parameterizations (Chikira & Sugiyama, 2010; Frierson, 2007; Moorthi & Suarez, 1992; Randall & Pan, 1993; T. Wu, 2012; G. J. Zhang & McFarlane, 1995; Zhao et al., 2018). Such adjustment of vertical temperature structures is facilitated by analytic solutions (Emanuel et al., 1994; Yu & Neelin, 1997) to develop tropical intermediate complexity models (Neelin & Zeng, 2000; Sobel & Neelin, 2006; Zeng et al., 2000) and has been found to be profound within deep convective areas by observations (Holloway & Neelin, 2007; Li et al., 2022; W. Wu et al., 2006; Xu & Emanuel, 1989).

Deep convection, often characterized by its robust updraft core and expansive cirrus anvil canopy, has predominantly been studied using satellite observations to discern its thermodynamic characteristics across temporal and spatial scales (Del Genio & Kovari, 2002; Feng et al., 2011; Houze et al., 2015). Collocating polar-orbiting and geostationary satellites enables the monitoring of three-dimensional thermodynamic structures within deep convection (Chakraborty et al., 2016; Chung et al., 2008; Takahashi & Luo, 2014), among which is the Mesoscale Convective System (MCS) playing a crucial role in contributing over half of tropical precipitation (Feng et al., 2021; Nesbitt et al., 2006; Roca et al., 2014; Schumacher & Rasmussen, 2020; Yuan & Houze, 2010). MCSs behave differently with and without diverse deep convective cores (D. Wang et al., 2020; Zheng et al., 2018) while algorithms utilizing geostationary satellites have been employed to track MCSs, generating comprehensive global datasets (Feng et al., 2021; Fiolleau & Roca, 2013; Huang et al., 2018).

Despite extensive validations showing the proximity of tropical temperature perturbation profiles to those constrained by the CQE theory, the spatial domains were confined to specific sites or regions across observations (Holloway & Neelin, 2007; Li et al., 2022; Nie et al., 2010) and models (Lin et al., 2015; X. Wang et al., 2022). This leaves an intriguing gap unexplored: the immediate vicinity of tropical deep convection, presumed to be the primary force shaping temperature structures. To bridge this gap, a Lagrangian framework integrating an MCS-tracking database and CloudSat retrieval to pinpoint the center of deep convective systems is proposed to quantitatively assess when the temperature perturbations, within a certain radius relative to the center, adhere to the CQE structure.

2. Data and Methodology

2.1. Data

The CloudSat satellite is equipped with a 94 GHz Cloud Profiling Radar (CPR) that detects cloud and precipitation particles. The CPR has a high-resolution footprint of approximately 1.7 km along track and 1.3 km across track with a vertical resolution of 480 m. Its active sensing capabilities enable the radar data to provide detailed vertical cloud structures. The Tracking Of Organized Convection Algorithm through a 3-D Segmentation (TOOCAN) is a specialized tool developed for detecting and tracking MCS using infrared imagery from geostationary satellites (Fiolleau & Roca, 2013). The clustering method within TOOCAN utilizes an iterative process across horizontal and temporal dimensions to decompose brightness temperature regions under 235 K into several MCSs by repeating growing regions starting at 190 K with a 5-K increment. To identify deep convection, radar reflectivity and cloud mask data from the CloudSat satellite's 2B-GEOPROF product (Marchand et al., 2008), and morphological parameters of MCS mass center locations (latitude, longitude, time) along the life cycles from the TOOCAN database, are employed.

However, to obtain the most accurate representation of the atmosphere's true state, atmospheric reanalysis combining observational data with numerical models, is commonly utilized. In this study, we examine the hourly temperature field using the European Center for Medium-Range Weather Forecasts' fifth global reanalysis (ERA-5), which is generated based on the Integrated Forecasting System (IFS) Cy41r2 with a four-dimensional variational data assimilation scheme (Hersbach et al., 2020). In addition to temperature data across all available pressure levels, we also extract total precipitation data from the ERA5 to adjust the time coordinate for analysis. Both TOOCAN and ERA-5 data are harmonized to a temporospatial resolution of 0.25° × 0.25° and hourly increments to ensure their congruence.

Within the scope of this study, only MCS objects with track of the mass center confined within 30 degrees north and south in latitude over lands and oceans are examined. To align with the data availability across the CloudSat, TOOCAN, and ERA-5, we analyze data only for the year 2013.

Note that only the ascending (daytime) observations of CloudSat at around local time 13:30 is used here due to its battery anomaly since 2011.

2.2. Locating centers of deep convection

In this manuscript, we focus on well-developed MCSs that contain at least one deep convective core (DCC), detected by CloudSat, within its coverage at any given time during its lifespan recognized by TOOCAN. The DCC criteria encompass continuous radar echo from cloud top to within 2 km of the surface, an echo of at least 10 dBZ above 10 km, and an attaching anvil horizontally spanning over 20 km with its base above 5 km, similar to previous works (Takahashi & Luo, 2012; Takahashi et al., 2017, 2021, 2023). This integration of continuous monitoring from geostationary satellites and vertical-penetration ability from polar-orbiting satellite prevents misclassification based solely on cold brightness temperature (Liu et al., 2007) and facilitates accurate tracking of deep convection centers. Note that the TOOCAN data over the western South Pacific is not available because the routine scanning schedule of the MTSAT-2 satellite, being operated during the study period, did not allow as frequent observations as optimal for cloud tracking in the southern hemisphere. Although the centers are ascertained using integrating satellite products, subsequent Lagrangian analysis exclusively relies on ERA-5 reanalysis data due to its capacity to capture temporal evolution across a vast three-dimensional domain equally inside and outside clouds unlike infrared satellite sounding.

2.3. Characterizing temperature perturbations near deep convection

All following calculations and illustrations in this section are conducted within a specified radius, or the distance from the deep convection center chosen from 1 to 10 degrees, from the convection centers. For each convection object, we identify the peak precipitation hour at every grid throughout its life duration and extract the hourly temperature profiles within 24 hours before and after accordingly. The temperature perturbations are obtained by subtracting a mean temperature profile averaged over the relative [-24,24] hours within the radius. To investigate temperature behaviors influenced by convection intensity, a threshold for peak precipitation exceeding a specific percentile, ranging from 80% to 99%, is calculated and applied across the radial distance, relative hours, and convection objects. For each hour, the temperature perturbations conditioned on the peak precipitation over the 329 observed deep convective objects at each level are regressed against those in the free troposphere, defined between 850 and 200 hPa, resulting in a single regression coefficient. The vertical profile of regression coefficients, same as that presented in Holloway & Neelin (2007), depicts the leading hourly pattern of temperature perturbations observed within the radius, reflective of a specific convection intensity.

2.4. Quantifying similarity of temperature perturbations to the theoretical CQE structure

The theoretical temperature perturbation profile constrained by CQE, to be compared with the leading observational profile, is referred to as the A-profile afterwards for simplicity. The A-profile is a function of temperature profile under assumptions of hydrostatic approximation, ideal gas law, and Clausius–Clapeyron relation (see detailed derivations in Li et al., 2022, modified from Yu & Neelin, 1997):

$$A(p,T(p)) \equiv \frac{T'(p)}{T'(p_0)} = \left(\frac{p_{LCL}}{p_0}\right)^{\kappa} \frac{1+\gamma\left(T(p_{LCL})\right)}{1+\gamma\left(T(p)\right)} \exp\left(-\kappa \int_{p}^{p_{LCL}} \frac{1}{1+\gamma\left(T(p')\right)} d\ln p'\right), p \leq p_{LCL}, \quad (1)$$

and

$$A(p,T(p)) \equiv \left(\frac{p}{p_0}\right)^{\kappa}, p > p_{LCL}, \quad (2)$$

where p is pressure, T temperature, T' the temperature perturbation from climatology, p_0 the reference level, p_{LCL} the lifting condensation level (LCL), $\gamma \equiv \frac{\varepsilon e_s {l_v}^2}{c_{pd} p R_v T^2}$ with $\varepsilon \equiv \frac{R_d}{R_v} = 0.622$ the ratio of gas constant for dry air R_d to that for water vapor R_v, e_s the saturation vapor pressure with respect to liquid, l_v = 2.5×10^6J/kg the latent heat of vaporization, c_{pd} = 1004 J/kg/K the specific heat of dry air at constant pressure, and $\kappa \equiv \frac{R_d}{c_{pd}}$.

For simplicity, the individual A-profile is calculated with p_0 = 1000 hPa and p_{LCL} = 950 hPa by input of temperature profile interpolated to a 5-hPa interval at each grid and hour, without considering entrainment. To compare with the regression coefficient profiles, the A-profile is averaged within the [-24, 24] hours and within the given radius, then normalized to have unity root mean square over the free troposphere. Unless specifically noted, the term A-profile refers to the normalized A-profile hereafter. These settings are considered practical given the robust statistics of A-profiles in the tropics and the nature of A-profile illustrating proportions between vertical levels (Li et al., 2022). Finally, to quantify similarity between the A-profile and regression coefficient profile, vertical spatial correlation and root-mean-square deviation (RMSD) are calculated over the free troposphere.

3. Results and Discussions

3.1. Spatial distribution of temperature perturbations extracted near deep convection

Prior to comparing the A-profile and regression coefficient profile for their similarity, we explore the geographical distribution of collocated deep convection distribution to comprehend where the temperature perturbations are analyzed.

Figure 1a shows the count of extracted temperature profiles spanning [-24, 24] hours near tropical deep convection within a specific radius of 8 degrees from the deep convection centers, irrespective of precipitation intensity. The 8-degree radius is selected because it represents the maximum distance where the CQE constraint on temperature appears valid, as later detailed in section 3.3. The pattern generally corresponds to the ITCZ climatology, with more deep convection over the continents, especially the Amazon and west Africa, compared to the oceans. To further examine the temperature structure in conjunction with extreme precipitation, Figure 1b manifests the number of extracted samples over grids where peak precipitation exceeds the 99th percentile of all instances. Similarly, it captures a greater prevalence of extreme convective columns over continents than over oceans. The sensitivity tests with different radii demonstrate no significant changes on the geographic patterns in both cases (not shown), where the land-sea contrast of deep convection occurrences has been observed by previous studies (Liu & Zipser, 2005; Liu et al., 2007; Wang et al., 2019; Takahashi & Luo, 2014; Takahashi et al., 2017).

Note that Figure 1b does not mark where mass centers of deep convection or intense DCCs locate but directly pinpoints the grids collocated with intense precipitation within the specified 8-degree radius. Compared to an examination at the MCS scale, which analyzes every grid within the radius of top 1%-precipitating MCSs (not shown), this analysis at the individual grid level notably reduces noise among temperature perturbations. Such a difference likely arises due to inhomogeneous precipitation pattern within MCSs and the spatial discrepancy between the satellite-identified mass center and the ERA-5 precipitation center. The missing data over the western South Pacific, roughly between 115°E-175°E, may appear concerning because of frequent identification of DCCs (Takahashi & Luo, 2014; Takahashi et al., 2017). However, this region contributes relatively less to the global occurrence of tropical deep convection observed with coexisting high radar echo top height and low cloud-top brightness temperature (Liu et al., 2007). Therefore, while the absence of data poses a constraint, its impact on the study's outcomes and conclusions could be regarded as minor.

3.2. Leading observations and their similarity to the CQE theoretical structure

To derive the representative profile of observational temperature perturbations for comparison with the A-profile, or the CQE theoretical structure, we adopt the regression method from Holloway & Neelin (2007). Figures 2a-2g display the A-profile (dashed line) and leading observational patterns (colored lines) obtained through the regression at specific hours relative to the peak precipitation with a 7-hour interval, and Figure 2h collects all these profiles for a comprehensive comparison. Note that the profiles are calculated using temperature profiles conditioned on the 99th percentile peak precipitation (8.337 mm/hr) within an 8-degree radius of the deep convection centers, corresponding to the 10555 occurrences distributed in Figure 1b. To quantify the similarity between the regression coefficient profile and A-profile, Figure 2i showcases the time series of RMSD and vertical spatial correlation, both computed over the free troposphere between 850 and 200 hPa at each hour. Of special note is that the vertical spatial correlation is identical to the cosine similarity between profiles, and hence a positive correlation suggests a leading temperature perturbation profile that increases with height, mirroring the A-profile pattern within the free troposphere. All correlations mentioned in the text refer to the vertical spatial correlation.

Throughout most hours, the leading temperature perturbations tend to decrease with altitude in the free troposphere, opposing that seen in the A-profile, as depicted in Figures 2a-2c and 2e-2g. This leads to negative correlations and elevated RMSD in Figure 2i, suggesting that at an hourly scale or within a day, the CQE principle is mostly limited (Donner & Phillips, 2003; Zhang, 2003; Lin et al., 2015). In contrast, the highest correlation and lowest RMSD occur at the peak hour, flanked by abrupt increases within the [-4, 2] hour range. This is consistent with Figure 2d, which captures similar increasing perturbations with height between both profiles over the free troposphere, remarkably closely aligned between 700 and 300 hPa. The convective cold top, marked by a negative minimal perturbation around 100 hPa (Holloway & Neelin, 2007), remains consistently robust across all the hours. All the observational characteristics mentioned above hold true when assessed across different radii and peak-precipitation thresholds within the [90^{th}, 99^{th}] percentile range except for the higher correlations found for tighter radii and stricter thresholds (not shown). The rest of the manuscript will exclusively utilize the correlation to assess the CQE validity on temperature, as RMSD exhibits a similar response with opposite trend.

3.3. CQE validity as a function of relative hour, relative distance and peak precipitation percentile

We have demonstrated how top-1%-precipitating temperature perturbations align with the A-profile near deep convection, focusing on evolution of the vertical leading patterns. To provide a more comprehensive scrutiny, we validate the proximity of temperature perturbations to the CQE structure using spatial vertical correlation as a function of the hour relative to peak precipitation, distance relative to the deep convection centers, and the threshold percentile of the peak precipitation.

Figure 3a suggests that the CQE robustly constrains the leading temperature perturbations within the [-1, 1] hour. The positive correlation reaches the farthest distance of 8 degrees during the peak hour, along with the maximum correlation of ~0.87 among all hours. The robustness of the CQE constraints on temperature within the 2 hours aligns with the timescale of convective adjustment commonly considered (see section 5b in a review of Arakawa, 2004). This supports the CQE principle that convective adjustment is relatively fast compared to large-scale forcing. Interestingly, the influence of the CQE on temperature appears more profound one hour before the peak precipitation, where the positive correlation reaches 7 degrees, compared to one hour after, where it reaches 3 degrees. Such asymmetric horizontal extent of validity can be observed by conditioning on percentiles higher than 96% (not shown). The CQE constraints on temperature quickly deteriorate after one hour following the peak precipitation, causing temperature perturbations to deviate from the CQE more rapidly than the build-up of positive correlations before the peak hour. This aligns with the observations that the peak of the first baroclinic mode, or deep convective mode favoring the CQE structure, is followed by the peak of second baroclinic mode, which on the contrary disfavors the CQE (Masunaga & L'Ecuyer, 2014).

Notably, other positive correlations appear around [-17, -15] and [12, 14] hours, primarily confined within a 1-degree radius. The hourly time series of maximum precipitation among the top 1% precipitating grids suggests that this phenomenon is likely due to a few extreme precipitation events which happen to peak around these hours (not shown) while these minor peak correlations are more pronounced when considering a smaller radius and higher peak precipitation (not shown).

Figure 3b demonstrates that during the hour of peak precipitation, only the leading temperature perturbations with the top 10% peak precipitation exhibit a comparable pattern of increasing perturbations with height, akin to the CQE structure within a 1-degree radius, while only those in the top 5% extend beyond 1 degree. This suggests that not all convective objects can effectively adjust the neighboring temperature through the CQE constraints, but only the extreme ones among deep convection. This is consistent with the "circus tent" concept, which suggests that deep convection with the highest free-tropospheric moist static energy or temperature play a dominant role in convective adjustment processes in the tropics (Williams et al., 2023). The high threshold of peak precipitations and the minor peaks of positive correlations in Figure 3 both reinforce our understanding that most of the CQE constraints arise from a very small fraction of deep convection.

4. Concluding Remarks

Although previous studies have extensively examined the validity of CQE on temperature, many of them have focused on specific spatial domains or sites, rather than directly addressing the source of CQE constraints—deep convection. This study aims to investigate the evolution of leading temperature perturbation patterns near deep convection, consisting of MCSs identified by stationary satellites and deep convective cores observed by the CloudSat at a time. By employing a Lagrangian framework following the deep convection centers, this approach enables the quantification of when, where, and to what extent these perturbations resemble the CQE structure. Our key findings can be succinctly summarized as follows:

- (When) Conditioned on the top 1% peak precipitation and within the relative [-1, 1] hours,

- (Where) temperature perturbations obeying the CQE structure, defined as a positive vertical spatial correlation between the free-tropospheric leading observational and analytic theoretical profiles, reaches a distance up to 8 degrees,
- (To what extent) accompanied by higher correlations before the peak precipitation than after, with a maximum correlation of ~0.87 during the peak hour.

These results suggest that temperature perturbations near deep convection are rapidly adjusted towards the CQE structure in a few hours, consistent with the idea that the weak temperature gradient approximation allows tropical gravity waves to rapidly propagate strong signals from deep convection to affect the surrounding environmental temperature (Ahmed et al., 2021; Sobel et al., 2001; Y. Zhang & Fueglistaler, 2020). Within such a short timeframe, on the order of an hour, the CQE's influence on temperature is noticeable only when analyzing grids where peak precipitation exceeds the 90th percentile, implying that only a small fraction of deep convection is capable of influencing the neighboring temperature over distances greater than 100 kilometers. Temperature perturbations with the top 1% peak precipitation near deep convection conform to the CQE structure up to 8 degrees from the centers during the peak hour, as one might expect from the typical Rossby radius of deformation, which ranges from hundreds to thousands of kilometers. Most importantly, this study underscores the dominant role of deep convection with extreme precipitation in shaping the leading patterns of tropical free-tropospheric temperature. One might consider the possibility that the CQE theory has been considered valid at a timescale longer than a day because the occurrence of extreme deep convection, which is capable of adjusting large-scale temperature over a long distance, is not frequent within a day.

The current study provides an interesting angle in understanding how valid the CQE constrains tropical free-tropospheric temperature near the deep convection in a Lagrangian view. However, owing to the requirement of monitoring vertical temperature structure changes with a high spatiotemporal resolution, the ERA-5 reanalysis data is utilized here instead of comparable satellite observations as those used during the collocation of deep convection. Also, although the collocation strengths our confidence of collecting well-developed MCSs coincided with deep convective cores at a certain time point, one cannot assure that deep clouds always exist around the mass centers along the evolution. Overall, we consider the methodological framework to be highly optimized for such an analysis but future work improving the collocating procedures and expanding the studying period, even towards how the CQE validity might change under a climate-change scale, is needed to further understand the relationship between the CQE and deep convection.

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Data Availability Statement

Information about the CloudSat can be accessed through the CloudSat Data Processing Center hosted at: https://www.cloudsat.cira.colostate.edu/ while the level-2 radar data used here is available at: https://www.cloudsat.cira.colostate.edu/data-products/2b-geoprof. Details regarding the Tracking Of Organized Convection Algorithm using a 3-dimensional segmentation (TOOCAN) can be found at https://toocan.ipsl.fr/ while the database descriptions are available at https://doi.org/10.14768/20191112001.1. The hourly temperature and precipitation data from ERA-5 are obtained from https://doi.org/10.24381/cds.bd0915c6 and https://doi.org/10.24381/cds.adbb2d47, respectively.

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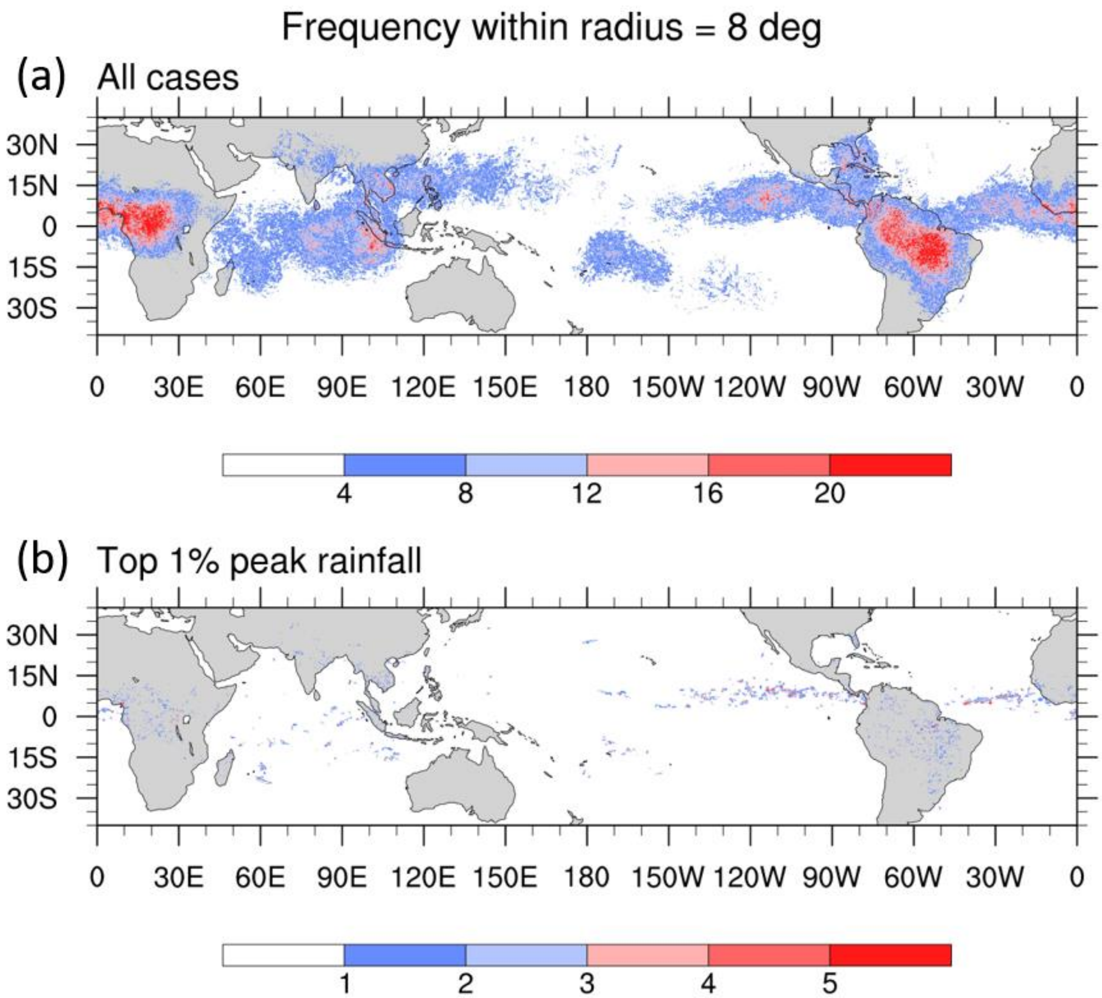

Figure 1: Occurrences of extracted temperature profiles within an 8-degree radius of tropical deep convection centers for (a) all instances regardless of peak precipitation and (b) instances where the peak precipitation surpasses the 99^{th} percentile (c.f., method) in the year of 2013.

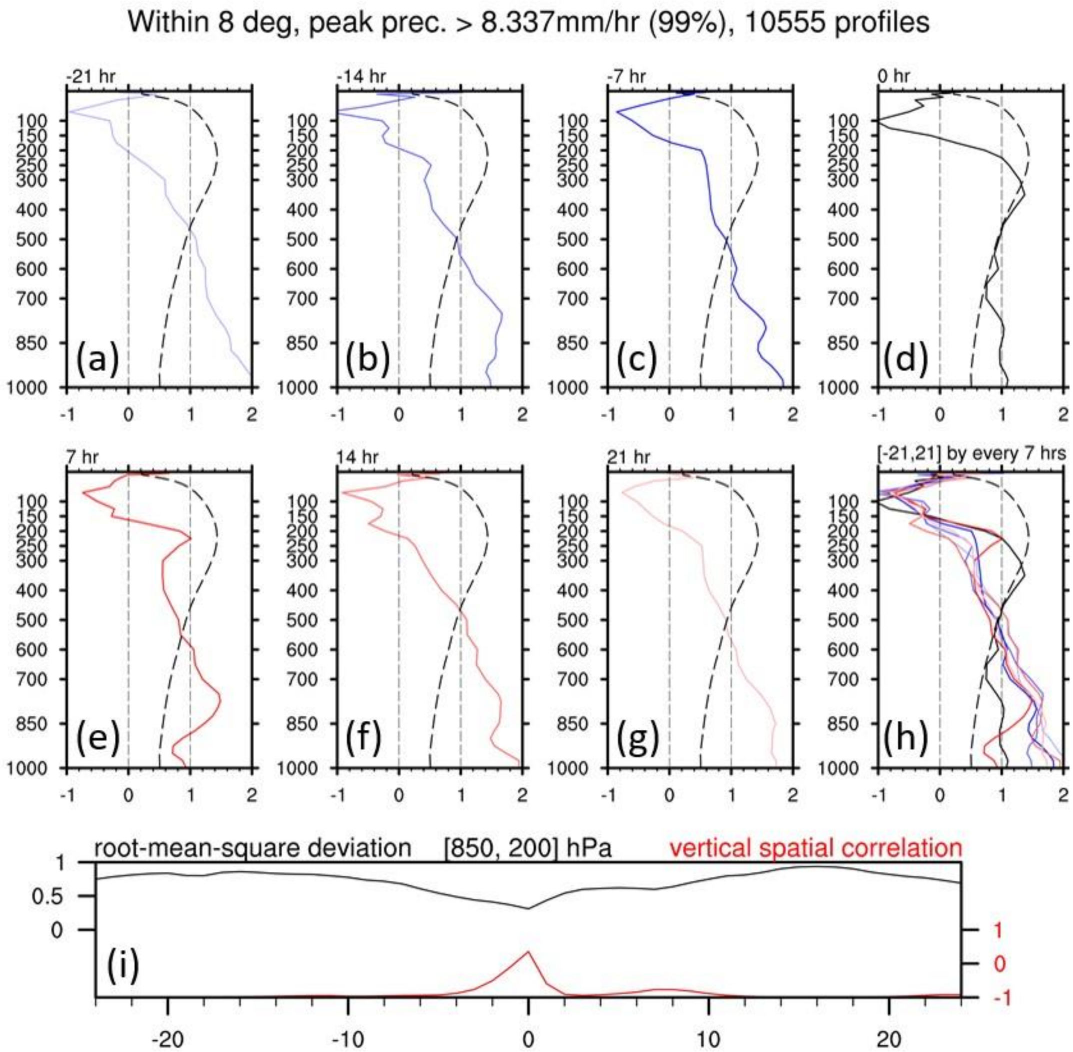

Figure 2: (a) The A-profile (dashed) and vertical profile of regression coefficients (colored) of the temperature perturbations within an 8-degree radius conditioned on the peak precipitation exceeding the 99th percentile at each level against the free troposphere. The regression coefficient profile is calculated at -21 hour relative to the peak precipitation hour. (b-g) As in (a), but for -14, -7, 0, 7, 14, and 21 hours, respectively. Note that lighter colors indicate hours farther away from the 0 hour. (h) Collection of all the profiles shown in (a)-(g) for comparison. (i) The hourly time series of root-mean-square deviation (black) and vertical spatial correlation (red) between the A-profile and the regression coefficient profile over the troposphere.

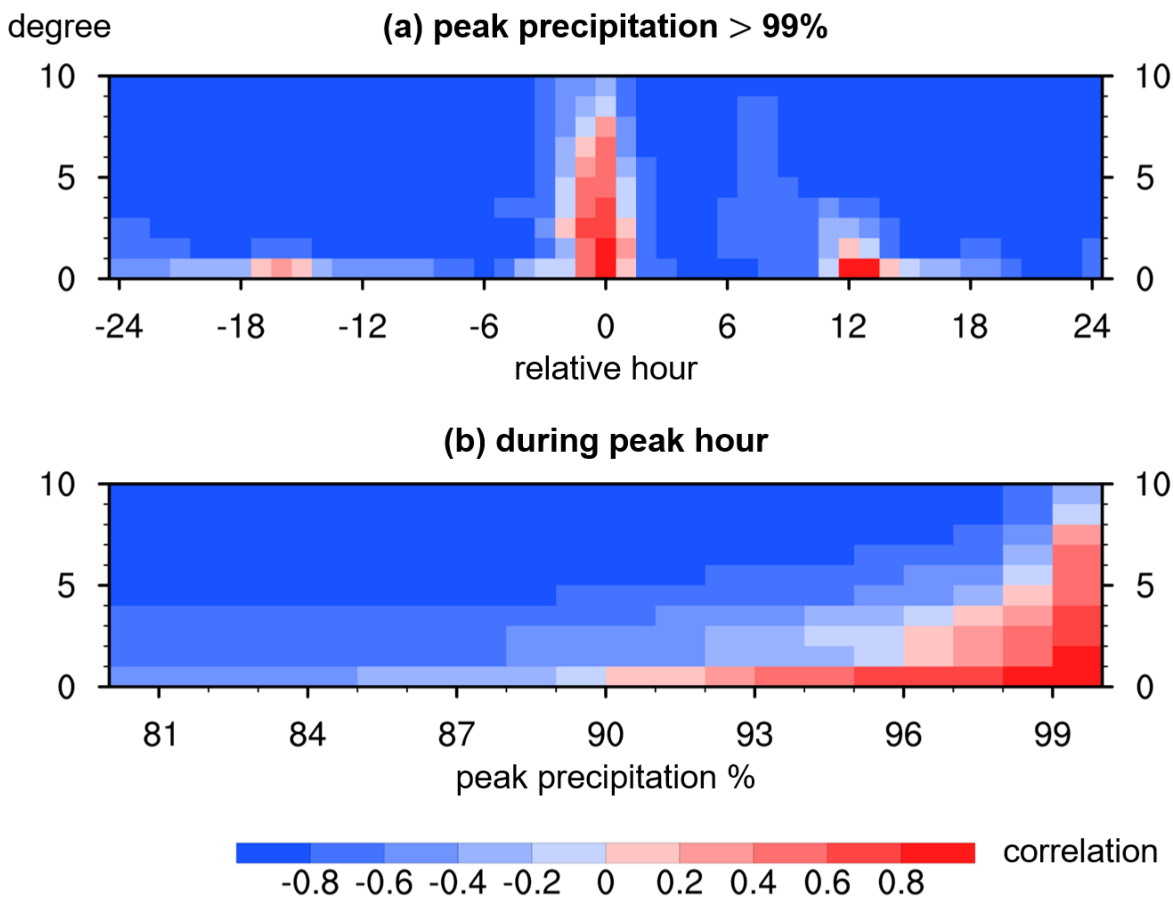

Figure 3: (a) Vertical spatial correlation between the regression coefficient profiles using temperature perturbations conditioned on peak precipitation exceeding the 99th percentile and the A-profile over the free troposphere. Each box indicates the correlation at a specific hour relative to the peak precipitation (x-axis, spanning from -24 to 24 hour in 1-hour increments) within a certain radius with respect to the deep convection center (y-axis, extending from 1 to 10 degrees in 1-degree increments). (b) As in (a), but the correlations are calculated at the peak hour using temperature perturbations exceeding different percentile thresholds of the peak precipitation (x-axis, ranging from 80% to 99% in 1-percent increments).