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Radar-derived Storm-to-large scale environment relationships: Observational constraints on the assumptions of Convective parameterization schemes in Numerical models

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Abstract

Radar-derived storm scale convection holds an important place in the scale hierarchy of tropical deep convective cloud systems as storms occupy major fraction and contribute to more than 90% of the convective precipitation. Nevertheless, accurately representing them in climate models requires an understanding of the relationships between the states of convective cloud ensemble and the large-scale environment. We investigate this relationship using 9 wet seasons of radar observations in a tropical station located at the eastern flank of Indian Summer Monsoon Trough. We find several key characteristics of convective storms are related with their own unique environments. The larger positive moisture convergence is associated with increased convective precipitation through increasing convective precipitation area. Numerous Convective storms are likely to occur in moist mid- tropospheric conditions, albeit those cells are less intense. On other hand, in a relatively drier mid-tropospheric conditions storms are observed to be fewer but more intense. CAPE is observed to affect cell area and cell number in a disproportionate way such that it has a stronger influence on intensity than areal mean property. Though our findings are statistically robust, we acknowledge significant variability in the relationships. Storm scale Convection bears a more systematic relationship with large-scale environment measures related to large-scale convergence compared to instability/energetics.

1 Introduction

Monsoon Convective cloud systems are multi-scale rain bearing system in the tropics with spatiotemporal scale ranging from an individual cumulonimbus clouds to meso-scale convective systems (MCSs). There is a long history on MCSs characteristics and know-how related to their dynamic/thermodynamic environment interactions using ground-based radar observation during the field experiments such as Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), Tropical-Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE), Dynamics of Median-Julian Oscillation (DYNEMO) as well as space-born radar observation program like Tropical Rainfall Measuring Mission(TRMM), Global Precipitation Measurement (GPM) [1]. However, the storms/cells within the MCSs occur at spatiotemporal scales much smaller than the larger-scale systems (i.e. MT) in a synoptic scale atmospheric environment like Monsoon regimes and remain very less explored over Indian Regions with few of its kind study [2]. Monsoonal MCSs contains few to more than 20 storms within them such that they occupy about 40% of convective area and contribute about 90% of the convective precipitation within an MCS [2]. Also the interrelationship between storm and MCS which is a multi-scale feedback nonlinear process strongly affect the large-scale environment through heating and drying the atmosphere [3]. Therefore, radar-derived storm-scale convection holds an important place in the scale-hierarchy of the tropical deep convective cloud systems. The nature of convection on these smaller scales as compared to the sizes of climate model grid box makes their interactions complex and therefore implicates the need for parameterization [4]. Nevertheless, accurately representing convective cloud ensemble in numerical weather and climate models stills remains a standalone problem. To parameterize convection in general circulation models several parameterization schemes is been used and such schemes are based on the relationship between the large scale atmospheric state at the model grid box scale and the convective scales [5]. There are two ways of parameterizing convection in numerical models: Conventional and stochastic schemes. In conventional schemes, assumption used is the Convective Quasi-Equilibrium (QE) in order to close the model equation such that two scales are in quasi-equilibrium condition, resulting in several large-scale variables as convective characteristics of the environment that relate to the state of the convective cloud ensemble. The large-scale variable so proposed serves as predictors of the convective scale. Those include moisture convergence [6], stability measures such as convective available potential energy (CAPE) and convective inhibition (CIN) [7], and more recently, midtropospheric humidity [8]. Nevertheless, there exists variance in the relationship between convective and large scale at the smaller convective scales and that provides the platform for stochastic physics scheme (SPS). SPS is a scale-aware scheme that adapt automatically to different spatio-temporal scales and is a computationally cheaper alternate to increasing resolution. SPS is still in its early stage and going through sensitivity study. Therefore, the main objective of this study is to present observational evidence aimed at helping to constrain convective schemes with implications for both convectional as well as stochastic schemes. Such study is highly implicative over the eastern edge of Indian summer monsoon trough region where convective activity is largely controlled by the synoptic scale features like monsoon Low Pressure Systems (LPS) forming over the Bay of Bengal and passes over the region. We attempt to partially fill this gap by explicating the relationship of the large scale convective environment and the convective state properties of observed storms using unprecedented, comprehensive radar observations and the large-scale convective environment.

2 Data, Analysis, and Methods

This study requires two time harmonized data sets of small scale convective storm ensemble properties and large-scale environment. For the former, we use have used high-resolution volumetric reflectivity measurements form a S-band Doppler weather Radar(DWR) deployed in the close vicinity of the eastern flank of Monsoon Trough (MT) zone over Kolkata (22.57°N, 88.35°E, 35m AMSL) for nine wet season. Detail technical description and data processing can be found in [9]. The polar coordinated volume scan radar observations are post-processed using a Delaunay triangulation scheme to interpolate it onto 3D Cartesian coordinate with horizontal and vertical resolutions of 1 km and 500m respectively by implying the Radx2Grid-algorithm of Radx application developed at the Research Application Laboratory, National Centre for Atmospheric Research, USA [10]. Further, a two dimensional data set, Constant Altitude Plan Position Indicator (CAPPI) is generated from the 3D radar volume scan data in order to display onto two dimensional surfaces at a constant altitude above the earth surface. A convective storm is identified by considering the CAPPI at 2 km with a reflectivity threshold of 35 dBZ (proxy for intensity of the convective system) in a volume of at least 30 km^3 and then tracked in space at discrete time steps of each canonical sweep (i.e., 10 min) by using an object oriented Lagarangian tracking algorithm TITAN (Thunder-storm Identification Tracking Analysis and Nowcasting) developed by [11]. Storm properties such as echo top height, Mean and Maximum Reflectivity, area, volume, lifetime, propagation speed and direction are obtained using a subroutine of TITAN algorithm called Tracks2Ascii and a long term climatological statistics of convective storm properties over the eastern MT region is generated. We have used Era5 reanalysis products averaged over an area of approximately 300×300 km^2 for large-scale environment. We considered key large-scale parameters that have frequently been associated with the convective ensembles with an aspiration to understand scale relationships in such a way that parameterizations of convection in the climate models could be improved. Those are CAPE, relative humidity at 650, and moisture convergence. To make large-scale environment and small-scale convective cells concurrent in time, we interpolated linearly 6-hourly reanalysis products to the temporal resolution of the radar data.

3 Results and Discussion

3.1 Storm-to-Large scale Relationship: Dynamics, Thermodynamics and Stability

Given the large-scale variables as mentioned in the above section, the investigation is divided in to three overall categories: dynamics, thermodynamics, and atmospheric stability. The chosen variables are vertically integrated moisture convergence, mid-tropospheric relative humidity and CAPE as representatives of dynamics, thermodynamics, and Stability respectively.

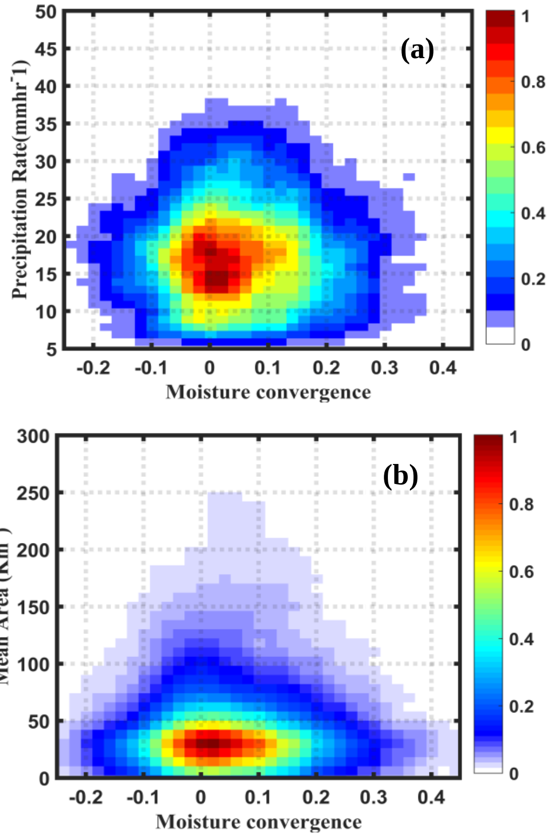

Figure 1 2D Histogram of (a) Moisture convergence and Convective Precipitation Rate (b) Moisture Convergence and Mean Area

We explore how the small-scale convective state storm stratifies with the mid-tropospheric environment. We achieve this by constructing 2D histogram of small scale convective storm parameters as function of large-scale environment. Figure 1(a) and 1(b) explain the relationship of convective precipitation and area with the moisture convergence. There is generally higher (lower) convective precipitation associated with positive (negative) moisture convergence. A similar relationship of area can be observed with moisture convergence as that of convective precipitation rate recommending that the larger moisture convergence is associated with increased Convective precipitation through increasing convective precipitation area. This result provides observational support for a finding from cloud-resolving modeling studies that convection responds to an increase in prescribed model "forcing" predominantly through an increase in convective area and also confirms other observational finding over a similar monsoonal setting over Darwin, Australia [12, 13]. However, some of the higher convective precipitation occurs when there is net divergence and hence likely subsiding. Therefore, the relationship observed here with two datasets does not explain the cause and effect of convection used as the fundamental assumptions in convective parameterization that is Convective heating and precipitation induce moisture convergence, and in turn high moisture convergence trigger convection more likely [5].

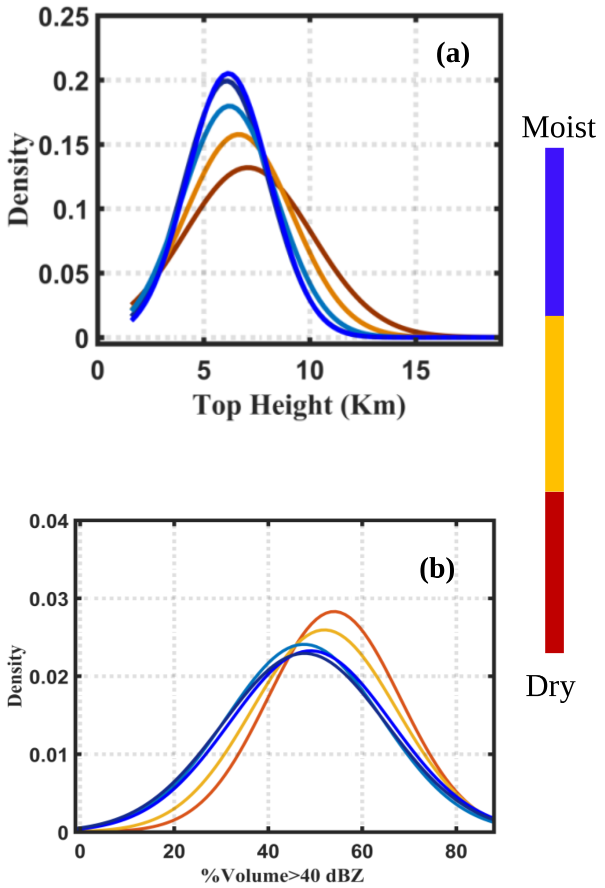

Figure 2 Distribution (Kernel density estimates) for (a) 35 dBZ Top Height and (b) "% Volume >40 dBZ" as functions of RH650.

Moving on to the relationship involving mid-level humidity (2D histogram, not shown here), we notice lowest mid-tropospheric relative humidity is found when there are very few cells occurrence. To understand the relationships of these rarely occurring cells in a drier midlevel conditions we look in to different perspective on how convective storm varies as a function of mid-tropospheric moisture in different range bins and shown in the figure 2 (a) and (b). The storm top height and intensity parameter probability distributions are found and sorted into deciles based on midlevel moisture. Blue colors represent normalized distributions with the largest moisture and red-to-yellow colors with low moisture. Probability distribution of top height as a function of humidity, explains that the deepest cells, however very few in numbers, are associated with driest conditions. While, most populated cell top heights are in Congestus mode, these cells are associated with moist midlevel conditions.

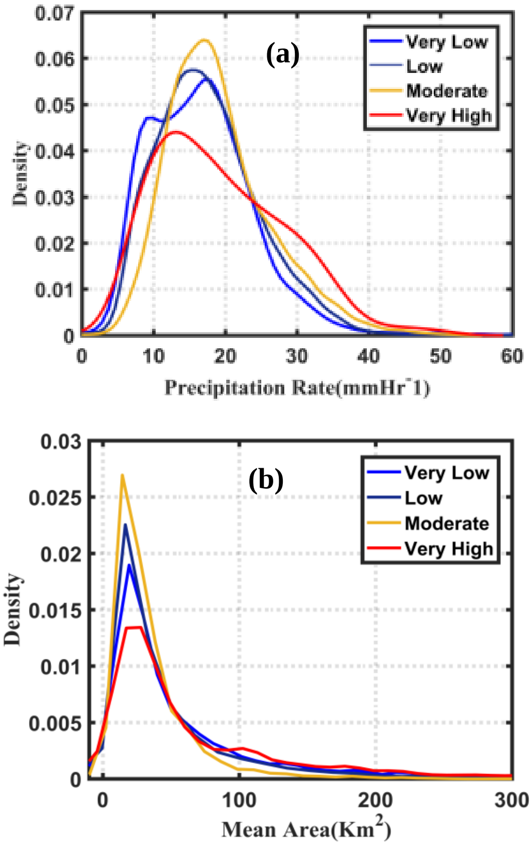

Figure 3 Distribution (Kernel density estimates) for (a) Cell area and (b) Precipitation rate as a function of CAPE.

Also these most populated cells tend to have relatively lower value of maximum reflectivity as well as "% Volume >40 dBZ". As the environment tends to dry, there is a right shift in the distribution towards higher value of maximum reflectivity, height of maximum reflectivity and rain rate intensity. This implies that in a moist environment, convective cells are numerous with less intensity; however, in drier conditions, while there are fewer convective cells, the individual cells are likely to be more intense.

Next, we examined the relationship involving instability/energetics parameter say CAPE (Figure 3). There is no such systematic relationship between storm scale convection and CAPE is observed which an assumption is made in the convective parameterization scheme known as CAPE closure. While storm area likely to increase with increasing CAPE values for low to moderate values, there is a tendency of decreasing area in higher range bins of CAPE. The pattern of the relationship of cell area to CAPE is also very similar to the relation of Precipitation rate and CAPE (figure 3a and 3b), indicating a stronger influence of CAPE on intensity than on area-mean rainfall. Therefore, CAPE influences convective cell area and number in a disproportionate way such that it is a good indicator of convective intensity rather than areal mean convection. Thus, CAPE is unlikely to be a good predictor for a connective parameterization, which aims at describing the area-averaged behavior.

3.2. Variability in the relationships: How stochastic is the MT Convection??

Though our findings are statistically robust, we acknowledge significant variance in the relationships which is quoted as a source of systematic errors arising from subgrid-scale fluctuations in the numerical model. One way to reduce such error and estimating the model uncertainty is to introduce the SPS in the convective parameterization. Since, Convective parameterization schemes aim at describing the area-mean behavior convection in the model grid-box; we defined areal mean convection in the equation (1):

$$P = \sigma I \quad \text{----- (1)}$$

Where P is Precipitation rate intensity, σ is precipitation area, and I is convection Intensity. Though the quantitative measures of the storm-environment scales relationship is not the goal this section, it is worthwhile to try and further explore some simple statistical properties of the relationships, and to see how stochastic the relationship is. Here, the goal is to examine whether storm scale Convection shows a more systematic relationship with measures related to large-scale convergence compared to measures related to energetics (e.g., CAPE). We achieve this by finding the mean and standard deviation of convective storm parameter I in different range bins of moisture convergence. Mean and standard deviation convective Intensity (I) values are calculated in range bins of moisture convergence grouped into 7 equally sized bins (figure 4). A close look on the figure 4 figure out that the mean and standard deviation of storm scale convection increases with increasing moisture convergence for positive values (strong external dynamic forcing) while a reverse relationship is observed in the negative (i.e., weak external dynamic forcing). Therefore, storm scale Convection bears a more systematic relationship with large-scale environment measures related to large- scale convergence compared to instability/energetics. The magnitude of the randomness in the convective strength and large-scale relationship is found to be decreasing as a function of the increasing large-scale dynamic forcing itself. This explains the selective nature of storm scale convection in the large-scale environment over an Indian MT region that the storm scale convection is likely to more deterministically relate to the large scale moisture convergence during strong external dynamic forcing (i.e. Monsoon). However, the relationship is more stochastic when the dynamic forcing is weak. Thus, we find a Stochastic to Quasi-deterministic transition nature of convection in the observations.

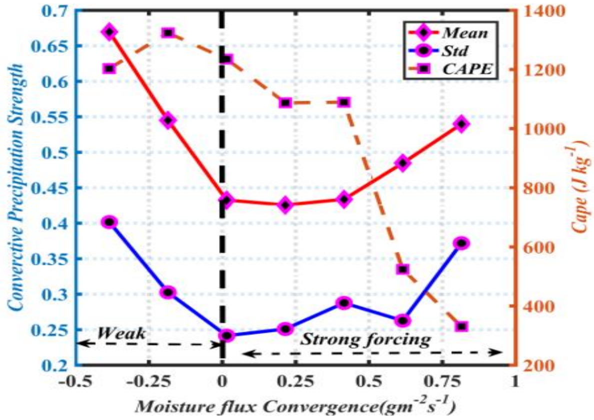

Figure 2 Mean and Standard deviation of convection intensity as a function of moisture convergence

Therefore, if we go for QE parameterization schemes in numerical models for Indian summer Monsoon Predictions the fluctuation arising in the relationship during the weak forcing condition may lead to miss the adequate representation of very strong localized convection with high CAPE (i.e. extreme events) and thus, it may underestimates the monsoon rainfall prediction.

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