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OBSERVED CHANGES IN ORGANIZED TROPICAL DEEP CONVECTION AS IDENTIFIED BY CLOUD REGIME ANALYSIS

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1 INTRODUCTION

The importance of organized deep convection is underscored by its association with high levels of rainfall. Despite occurring only about 5% of the time, it contributes to about half the amount of precipitation in the tropics (Tan et al., 2013) and is associated with extreme precipitation (Rossow et al., 2013). Aside from rainfall, organized deep convection has a critical impact on weather and climate such as through cloud feedbacks (Stephens, 2005), mesoscale convective systems (Houze, 2004), and tropical phenomena such as the Madden-Julian Oscillation (Zhang, 2005).

How organized deep convection will change in a warming climate has been the subject of some studies. For example, Chen et al. (2002) reported a change in organized convection during the 1990s by utilizing a variety of satellite and reanalysis product. Del Genio et al. (2007) used estimates of convective updraft speeds from a global climate model to associate an intensification of convection with global warming. Berg et al. (2013) employed high quality regional gauge data to quantify the increase in convective precipitation due to higher temperatures. However, purely observational studies on organized deep convection have been scant because of a lack of long-term and global measurement of variables that can reliably represent not just deep convection but its degree of organization.

One study of this nature is Tselioudis et al. (2010). By using a categorization of tropical cloud fields from satellite records that began in 1983, they discovered an increase in the frequency of organized deep convection by about 20%. However, their analysis is limited due to potential satellite artifacts in observing clouds from less organized deep convection. Here, we extend their analysis in two ways. First, we minimize artifacts by implementing a satellite zenith angle filter and thus broaden the scope to less organized modes of deep convection. Second, we divide their representation of organized deep convection into two components: one that is primarily deep convection and one that is primarily stratiform.

The goals of our study are twofold. One, we wish to investigate the details of this change in organized deep convection, not just in itself but also in relation to other modes of deep convection. Two, we wish to examine the spatial trends in the change of organized deep convection, which has the additional benefit of highlighting potential satellite artifacts. Together, our results will advance our understanding of the changes in deep convection from an observational perspective.

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2 METHODS

The International Satellite Cloud Climatology Project (ISCCP) D1 dataset provides statistical descriptions of clouds within 280 km $\times$ 280 km equal-area grids in the form of joint-histograms of their cloud top pressures and optical thickness since 1983 at three-hour intervals (Rossow and Schiffer, 1999). In the tropics, these joint-histograms are composed from satellite pixel measurements with an approximate horizontal resolution of 5 km at nadir from a network of geostationary satellites. Polar-orbiting satellites are used only when geostationary satellites are unavailable. In Jakob and Tselioudis (2003), the k-means clustering algorithm is applied to the joint-histograms to identify repeating patterns. In Rossow et al. (2005), this method is further improved upon by a set of criteria to determine the number of clusters. Applying this technique to daytime-averaged joint-histograms between 35° latitudes, cloud fields can be objectively categorized into eight cloud regimes (or weather states), of which three possess significant signals of deep convection (see Tan et al. 2013 for more information).

The three deep convective regimes, CR1, CR2 and CR3 (called CD, CC and IM in Tan et al. 2013), represent different degrees of organization of convection. CR1 has a prevalence of towering cumulus and deep stratiform clouds as interpreted in the joint-histogram of its centroid and describes features such as thunderstorms and mesoscale convective systems. It primarily inhabit regions of organized deep convection such as in the Intertropical Convergence Zone, the Tropical Western Pacific and Indian Oceans, and equatorial Africa and South America. Despite a low frequency of occurrence (FOC) of 0.055, it is associated with an exceptional levels of precipitation and is responsible for close to half the total precipitation in those latitudes (Lee et al., 2013; Tan et al., 2013). CR2 represents deep convection which is less organized than that associated with the widespread thick clouds found in CR1. It is predominantly composed of cirrus clouds, a fact highly apparent in the joint-histogram of its centroid (Figure 1), and has a FOC of 0.084. CR3 represents deep convection more isolated in its nature with a broad distribution of cloud tops concentrated in mid-troposphere (Figure 1). This cloud top signature suggests a considerable coverage of cumulus congestus clouds. It has a FOC of 0.142. CR2 and CR3 not only occur in locations of substantial populations of CR1 but also in surrounding regions. In Tan and Jakob (2013), they are found to arise in the vicinity of a deep convective signal marked by a high incidence of CR1 such as in the Madden-Julian Oscillation.

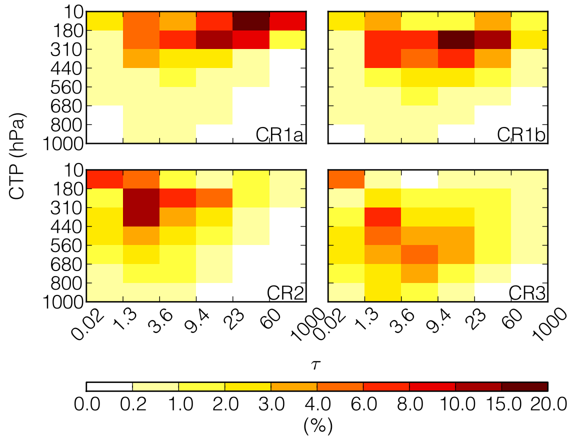

Figure 1: Joint-histograms of cloud top pressure (CTP) and optical thickness (τ) of the centroids of the four deep convective cloud regimes. CR2 and CR3 are derived by clustering the joint-histograms between 35° latitudes, while CR1a and CR1b are derived by re-clustering the joint-histograms belonging to CR1.

In Tselioudis et al. (2010), the FOC of CR1 in 15° latitudes was found to have increased by about 20% since 1983. One goal of this study is to further investigate this change. For this, we need a method to probe the changes within this regime. We discovered that a re-clustering of all joint-histograms belonging to CR1 produces two sub-clusters, CR1a and CR1b (Figure 1). These sub-clusters are consistent throughout a number of clustering attempts with different initial random seeds and hence are robust features of the tropical climate. CR1a occurs 25% of the time during this second clustering (i.e. it has an overall FOC of 0.014) and has a very high occurrence of deep convective clouds with some stratiform anvil. CR1b occurs 75% of the time (with an overall FOC of 0.041) and possess mainly thick stratiform anvil clouds. Both have very high cloud cover of 98.2% and 96.9%. Based on their centroids, we deduce that CR1a describes the more deep convective part of CR1 while CR1b describes the more stratiform part. This division of CR1 into two components allows us to better understand the CR1 change in Tselioudis et al. (2010).

We also wish to examine how CR2 and CR3 change. However, the direct approach of calculating the FOC over the entire tropics, as in Tselioudis et al. (2010), is not a viable option. This is due to the artifacts associated with ISCCP satellite changes occurring at the edges of the satellite coverage where the satellite zenith angles are high (Evan et al., 2007), an error apparent when spatial trends are plotted on a map. This artifact arises from the fact that, at higher zenith angles, more visible light passes through the clouds, such that very thin clouds are more likely to be detected. As this artifact only affects the threshold detection of clouds with low optical thickness, CR1 is largely immune to this error. For CR2 and CR3 (and, in fact, CR1b), we need a strategy to account for this satellite artifact.

Since the errors are primarily related to high zenith angles, we can set a threshold angle, beyond which the grid boxes will be discarded. This is possible because the ISCCP D1 dataset reports the cosine of the zenith angle at each grid box during each time step, which is constant most of the time but may vary at times due to occasional satellite drift. Figure 2 shows the contours of a zenith angle of 30° on a typical day, together with the five satellite positions in the tropics defined by ISCCP. We will restrict our calculation of the FOCs of the four regimes to grid boxes within these regions (i.e. zenith angle less than 30°).

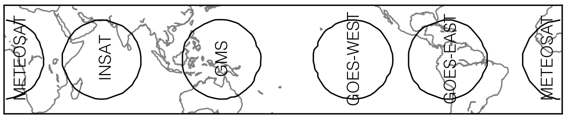

Figure 2: Contours of the reported satellite zenith angles at 30° on 1st January 2006. The labels indicate the satellite positions denoted by ISCCP.

Furthermore, as ISCCP D1 dataset also records the satellite ID code, we can readily identify, for each region, when there is a change in the satellite responsible for generating the joint-histograms. This change may come about due to events such as a permanent satellite replacement, temporary shut down (in which case the ID code is missing), or use of another satellite when the preferred one is unavailable. Tracking the satellite ID code provides an additional verification, informing us, for example, that a jump in FOC in each region coincides with change in ID code and thus flagging it as suspect.

3 RESULTS

3.1 Changes in Regime Frequency

Figure 3 shows the time-series of the frequencies of occurrence (FOCs) of all convective regimes, CR1, CR1a, CR1b, CR2 and CR3 in grid boxes with satellite zenith angle lower than 30°. First of all, the change of 13.6% for CR1 is of the same order of magnitude as the approximate 20% from Tselioudis et al. (2010). The difference is probably a consequence of our zenith angle filter reducing our region of study to a subset of that in Tselioudis et al.

(2010). This also explains the higher variability in our FOC due to fewer grid boxes studied.

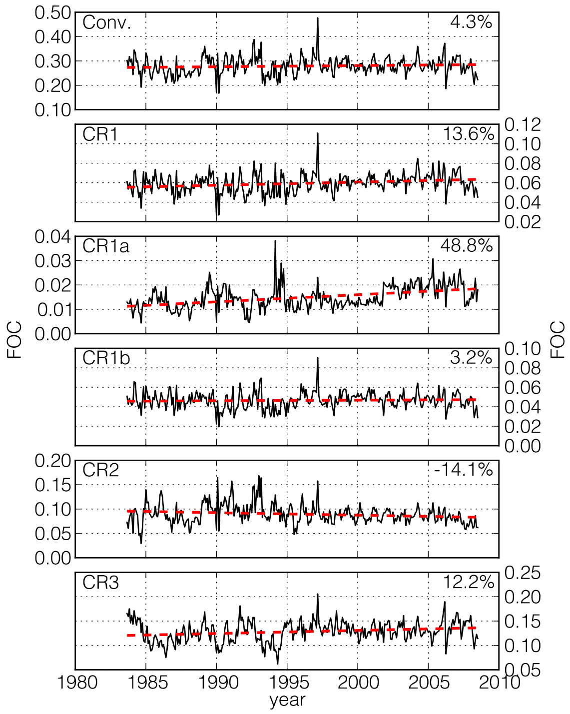

Figure 3: Time-series of the FOCs of all convective regimes, CR1, CR1a, CR1b, CR2 and CR3 in grid boxes with zenith angle less than 30°. The red dashed lines show the least square regression, with the total percentage changes from mean FOCs shown in the top-right corner.

Figure 3 indicates that CR1a, which represents organized deep convection with an abundance of deep convective clouds, has increased markedly by 48.8%. CR1b, which represents organized deep convection with thick stratiform anvils, has only a marginal increase of 3.2% that is not statistically significant ($p = 0.393$). Hence, the increase in CR1 observed in Tselioudis et al. (2010) and in our study is mostly due to more deep convective clouds (such as cumulonimbus) while the stratiform component of the organized deep convection has remain unchanged in terms of quantity. Furthermore, there is a decline in the population of CR2 by 14.1%, which is deep convection of a less organized nature. This change is substantial given the higher FOC of this regime than CR1a or CR1b. This translates to a decrease in the absolute FOC of CR2 of 0.0126 as opposed to an increase in the absolute FOC of CR1a of 0.0073. On the other hand, the monthly FOC of CR3 has risen by 12.2%, a lesser degree than CR1a. This regime, representing also less organized deep convection but with substantial congestus cloud, has the highest FOC of all regimes, and this percentage increase comes down to an absolute FOC change of 0.0158.

There is two suspicious jumps in the monthly FOC of CR1a, occurring around 2002 (upward) and 2007 (downward). These jumps are visible in most of the FOCs in the individual region, and they do not always coincide with a change in satellite ID codes (Figure 4). Such sharp changes are strongly suggestive of artifacts, and the absence of corresponding satellite changes hints at a modification in how the satellite retrievals are processed. This peculiarity in the signal is currently being investigated. Regardless, even if we were to remove the jumps and adjust the FOCs in intervening period downwards to match adjoining FOCs, the linear trend is still clearly increasing albeit at a smaller magnitude.

Comparing the changes over different surfaces, the rise (or, in the case of CR2, decrease in reduction) in FOC is higher over grids designed by ISCCP as land than over ocean (not shown). For CR1a, the rise is 72.5% over land and 45.3% over ocean. For CR1b: 25.5% and -1.8%. For CR2: 0.8% and -14.6%. For CR3: 34.9% and 5.2%. The reason for this land-ocean contrast is unknown.

The change in the FOC of all the deep convective regimes, i.e. CR1–3, is 4.3%, or an absolute value of 0.0119 (Figure 3). This gain is modest in contrast to that of CR1a, and is arguably statistically insignificant ($p = 0.116$). In this perspective, we conclude that deep convection has not increased in area coverage from Aug 1983 to Jun 2008, but has instead intensified from less organized forms to a more organized mode. This is reminiscent of similar studies on tropical cyclones, in which the number of weak cyclones has decreased in correspondence to the increase in the number of strong cyclones, such that the total number of cyclones globally remains constant (see, e.g., Webster et al. 2005).

3.2 Spatial Trends of Organized Deep Convection

The monthly FOC of CR1a in Figure 3 is calculated for all regions with a zenith angle of less than 30°. When performed separately, the missing data in the INSAT region surface prominently (Figure 4). The wide gap in the data meant that the linear regression, computed without the measurements before 1998 (blue line), is based on about ten years of data and hence unreliable for an analysis of long-term trend. Examining the FOCs of other regions, the greatest increase is in GMS, which contains parts of the Maritime Continent and the Tropical West Pacific, with a 90.3% gain. These are places with prevalent organized deep convection and has the highest FOC of CR1a overall. All other regions have more moderate increases of between 43.7% to 68.0%.

An interesting feature that emerges in Figure 4 is the shifts in organized deep convection associated with natural variability. The most prominent of these is the strong El Niño in 1997/1998, in which a drop in the monthly FOC of CR1a in GMS is accompanied by a bump in GOES-WEST. Annual cycles are also clear in METEOSAT and GOES-EAST, reflecting the seasonal changes in the respective regions.

Figure 4 also denotes the months with an occurrence of a change of satellite ID code (vertical lines). These satel-

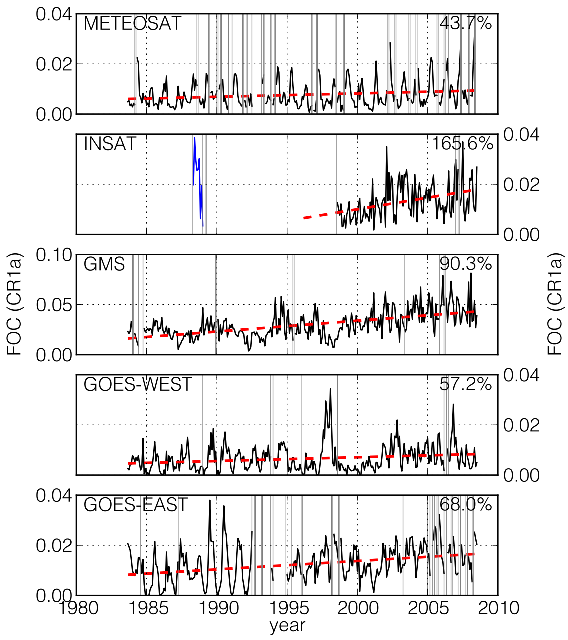

Figure 4: Time-series of the FOCs of CR1a similar to Figure 3, but for each individual regions of Figure 2. The vertical lines indicate a detected change in satellite ID code. For INSAT, the blue part of the data is not used for linear regression.

lite ID codes indicate the actual satellite used in constructing the joint-histograms and hence the regime. Changes in satellite ID codes are rife throughout METEOSAT and during two periods of GOES-EAST, but they are otherwise not a widespread issue. More importantly, these changes in satellite ID codes do not generally coincide with a jump in monthly FOC, implying that a change in satellite does not have a discernible effect on the monthly FOC of at least CR1a.

We can further examine the spatial trends of CR1a through the total change in absolute FOC of CR1a derived from a least square linear regression of the monthly FOC in each grid box (Figure 5). Here, the zenith angle filter is not applied. Two striking features emerge. First, the increase in FOC is highest in the Eastern Indian Ocean, Maritime Continent and Tropical West Pacific. These are regions with the highest FOC of CR1a, and yet the largest percentage increase also occurs here. This means that this region which often experience organized deep convection will witness an increase higher than other regions, bringing to mind a rich-gets-richer scenario.

Two, the Central Indian Ocean has a distinct pair of vertical arcs, which is indicative of artificial signal. According to the ISCCP records, the geostationary satellite for INSAT operated only for a brief period in 1988, and until 1998 the data for this region uses the neighboring METEOSAT and GMS satellites. As the ISCCP algorithm applies a cutoff zenith angle of 72.5° (see Section 3.1.2 of Rossow et al. 1996), this limit corresponds to the two arcs in Figure 5. Therefore, in calculating the trends in Figure 5, between

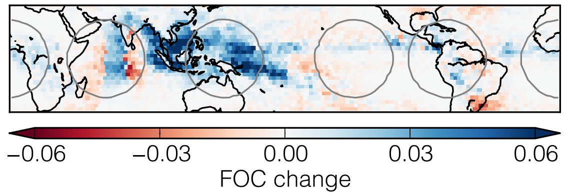

Figure 5: Total change in the absolute FOC of CR1a from the linear regression of the monthly FOC in each grid box. The 30° zenith angle filter was not applied, but the contours of 30° from Figure 2 are plotted as a reminder of the approximate locations analyzed in Figure 3.

the arcs (i.e. inside the column), only the INSAT geostationary data, mostly available after 1998, is used. Outside the arcs (or outside the column), both METEOSAT/GMS and INSAT retrievals are used. This difference in satellite source is responsible for this anomalous structure in the Central Indian Ocean. However, in our previous analysis (Figure 3), such artifacts are purged by the zenith angle filter, which would have excluded the retrievals from METEOSAT and INSAT. Indeed, when we applied the 30° threshold to the computation of Figure 5, the artifact disappeared (not shown). This demonstrates the validity of our approach of choosing grid boxes with zenith angles less than 30°.

4 DISCUSSION AND CONCLUSION

In the previous section, we showed that the organized deep convective regime with high populations of towering cumulus clouds, CR1a, has increased substantially in frequency over the period since ISCCP records began. This is accompanied by a weaker increase in CR3, a marginal increase in CR1b, and a decline in CR2, such that the FOC of all these deep convective regimes has not changed significantly. Furthermore, this increase in organized deep convection is disproportionate in different regions. For example, the GMS region where organized deep convection is most prevalent has also seen the largest percentage increase.

This increase in CR1a has a substantial impact on the climate system. CR1 has already been shown to possess an exceptionally high rainfall profile (Lee et al., 2013), be associated with extreme precipitation (Rossow et al., 2013), and is responsible for half the total precipitation in the tropics despite occurring only 5.5% of the time (Tan et al., 2013). Constructing the rainfall profiles of CR1a and CR1b separately, we observe that CR1a contributes to the higher end of the rainfall rates in CR1 while CR1b contributes to the lower end (not shown). This means that CR1a is associated with very intense precipitation. The increase in CR1a quantified here would hence have a profound impact on the distribution of precipitation in the tropics. Should this increase persist into the future, the incidence of extreme precipitation is likely to rise, a projection consistent with modeling studies (e.g. Muller 2013).

To further investigate this association between CR1a and precipitation, we utilize the Global Precipitation Climatology Product version 2.2 monthly rainfall product (Huffman et al., 2009). We first execute a least square linear regression on the precipitation rate in each grid box of the original 1° grids from 1984 to 2007, then interpolate using cubic spline to match the ISCCP 280 km × 280 km equal-area grid. This permits us to perform a spatial correlation between the two trends. We further restrict the computation to grids within the 'bubbles' in Figure 5 and ignore the INSAT region completely. This should reduce unphysical trends due to satellite artifacts, but it cannot completely eliminate the problem as these regions may contain grids with angles greater than 30° (these 'bubbles' are defined for a particular but typical day, and does not capture satellite drifts). The spatial correlation between the FOCs of CR1a and precipitation trends is 0.54. This imply that the changes in deep convective clouds of organized nature as represented by CR1a can explain more than half of the tropical rainfall trends in the past twenty-five years. Further work on this relationship is currently being pursued.

A conspicuous question that arises from Figure 3 is whether this increase in organized deep convection (and the corresponding decrease in less organized deep convection) is associated with global warming. This question cannot be concretely resolved using our approach, not least because the ISCCP record of twenty-five years is relatively short on climatic time scales. However, we make a first attempt at unraveling this problem by plotting the relationship between the monthly FOC of CR1a from Figure 3 and the monthly global mean surface temperature (GMST) from the NASA Goddard Institute for Space Studies Surface Temperature Analysis (Hansen et al., 2010). Note that this temperature data is a global-average and is not de-seasonalized. The relationship between the incidence of organized deep convection and GMST is moderate, with a correlation of 0.400 (Figure 6). This is not unexpected due to the complex and still poorly understood connection between temperature and organized deep convection. A lag-correlation analysis indicates that the highest correlation of 0.461 occurs when GMST leads the FOC of CR1a by five months. This establishes a modest association between GMST and the occurrence of organized deep convection. A consequence of this relationship is the potential climate feedback that may arise due to the strongly negative cloud radiative effect of CR1 (Oreopoulos and Rossow, 2011). This is an issue currently being investigated.

In conclusion, in an observational study first of its kind, we used cloud regime analysis with careful filtering of possible satellite artifacts to show that tropical convection has intensified into more organized modes over the past twenty-five years. The total frequency of deep convective regimes remains constant, but organized deep convective regime has increased in population at the expense of less organized deep convective regimes. This has a significant impact on the climate, as the organized deep convective regime is responsible for much of the tropical extreme precipitation. Preliminary investigations show

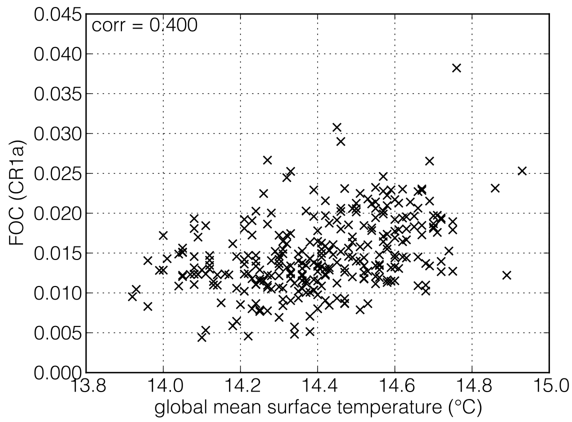

Figure 6: Scatter diagram of the relationship between monthly FOC of CR1a and global mean surface temperature.

that this change in organized deep convection can explain half of the tropical precipitation changes and is somewhat correlated with global mean surface temperature. If the relationship to global warming is firmly established, this means that climate change will lead to more organized deep convection and thus more intense rainfall.

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