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A three-hourly data set of the state of tropical convection based on cloud regimes

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[1] Tropical convection is a key driver in the climate system and is often identified using infrared satellite information or precipitation. Satellite-derived cloud regimes offer an alternative with potentially more informative distinctions between different types of convection. However, current ISCCP cloud regime data sets require visible satellite information and are therefore only available during daytime. We develop a convective regime data set for all three-hour intervals of the day using ISCCP infrared-only retrievals. We show that regimes derived in this way capture the essential properties of the original regimes, in particular, when identifying the state of tropical convection. We give examples for potential applications by illustrating the well-known Madden-Julian Oscillation and the diurnal cycle of convection in the framework of the newly derived regimes. The high temporal resolution, long record and global coverage of the regimes makes them a suitable tool for large-scale studies of tropical convection. **Citation:** Tan, J., and C. Jakob (2013), A three-hourly data set of the state of tropical convection based on cloud regimes, *Geophys. Res. Lett.*, *40*, 1415–1419, doi:10.1002/grl.50294.

1. Introduction

[2] Atmospheric convection is a critical mechanism in the climate system, responsible for the transport of heat, momentum and moisture at different scales. Given that it governs many tropical processes such as the formation of clouds and distribution of rainfall, and drives atmospheric phenomena such as the Madden-Julian Oscillation (MJO) that have significant weather impact globally, representing it accurately in models is vital. However, models exhibit sizable errors in tropical clouds and precipitation (e.g., [*Soden and Held*, 2006]) and perform poorly in terms of variability over different timescales (e.g., [*Lin et al.*, 2006]). These errors have been linked to how convection is represented by models, which often do not take spatial and temporal coherence into account. Therefore, understanding how convection organizes on the large scale may contribute to the improvement of model performance [*Yano et al.*, 2012].

[3] One avenue to investigate large-scale tropical convection is to use the International Satellite Cloud Climatology Project (ISCCP) D1 data set, which provides joint histograms of cloud top pressure and optical thickness for 280 km × 280 km grid boxes at each three-hourly sunlit intervals beginning from 1983 [*Rossow and Schiffer*, 1999]. By applying a clustering algorithm to these joint histograms, the ISCCP cloud distributions can be objectively classified into several cloud regimes (also referred to as "weather states"), identifying the recurring cloud patterns in the atmosphere [*Jakob and Tselioudis*, 2003; *Rossow et al.*, 2005]. (*Tan et al.*, On the Identification of the Large-Scale Properties of Tropical Convection using Cloud Regimes, accepted, *J. Climate*, 2013) have shown that some of these regimes represent distinct large-scale archetypes of tropical convection, including a convectively active regime dominated by deep stratiform clouds (CD), a convectively active regime dominated by cirrus clouds (CC) and an intermediate regime dominated by a mid-level congestus clouds (IM). They conjecture that these three regimes are observational proxies for the Stretched Building Blocks of tropical convection [*Mapes et al.*, 2006], representing respectively its "stratiform", "convective" and "congestus" modes. Understanding such organizational structures will advance our ability to dissect large-scale systems such as mesoscale convective systems on which total comprehension remains elusive.

[4] Many of the regimes are robust features of the ISCCP cloud fields, consistently manifesting in studies over different spatial ranges and time periods. They inhabit different environmental conditions [*Jakob et al.*, 2005; *Jakob and Schumacher*, 2008] and have been applied to the study of numerous phenomena such as the Madden-Julian Oscillation [*Chen and Del Genio*, 2008; *Tromeur and Rossow*, 2010], African Easterly Waves [*Mekonnen and Rossow*, 2011], cloud radiative effects [*Oreopoulos and Rossow*, 2011], precipitation [*Lee et al.*, 2012; *Rossow et al.*, 2012] as well as model evaluation [*Gordon et al.*, 2005; *Williams and Tselioudis*, 2007; *Williams and Webb*, 2009]. Cloud regimes can also be defined for other regions (e.g., [*Williams and Tselioudis*, 2007] and [*Haynes et al.*, 2011]) or with active measurements (e.g., [*Zhang et al.*, 2007]). However, the cloud regimes currently in use have a limitation: they rely on optical thickness information retrieved from the visible channel of the satellites used by the ISCCP algorithms and thus are not available at night. This reduces the above studies to "quasi-daily" timescales based on information usually averaged over daytime.

[5] Our goal is to overcome this constraint by developing a three-hourly data set of tropical cloud regimes. We evaluate our new technique by comparing the newly derived regimes with the original daytime-only results. We then investigate the efficacy of the new regimes as a tool in convective studies by applying them to the Madden-Julian Oscillation and the diurnal cycle of convection.

Additional supporting information may be found in the online version of this article.

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2. Methods

[6] Daytime-only tropical cloud regimes were derived by *Rossow et al.* [2005] using the methodology in *Jakob and Tselioudis* [2003]. For comparison, the original regimes are reproduced following their technique. First, a *k*-means clustering of the joint histograms of cloud top pressure (CTP) and optical thickness (τ) between 35°N and 35°S yields eight cloud regimes, each with distinct centroids. Second, each CTP-τ histogram is assigned to a regime by calculating the Euclidean distance of the CTP-τ histogram to all regime centroids and choosing the regime with the shortest distance. These regimes give cloud information on spatial scales of 280 km × 280 km, with temporal scales of a day, but based on daytime-only information as retrievals of optical thickness are not available at night. As our goal is to describe precipitating convection, the CD, CC and IM regimes introduced by (*Tan et al.*, accepted manuscript, 2013) are the three main regimes of interest in this study. They correspond to weather states 1, 2 and 3 in [*Mekonnen and Rossow* 2011] and *Oreopoulos and Rossow* [2011]. The full set of regimes can be found in (*Tan et al.*, accepted manuscript, 2013) and are virtually identical to the data set on http://isccp.giss.nasa.gov/etcluster.html.

[7] Cloud top pressure retrievals use infrared information only (referred to as "IR-only" henceforth) and are available at all times of the day. Previous studies have used the ISCCP IR-only information to find convective cloud clusters (see e.g., [*Machado et al.*, 1992]), but our goal here is to construct cloud regimes based on this IR-only information. Therefore, we need a procedure, corresponding to the first step in the original methodology, to derive the centroids for the IR-only information. There are several options for this. First, one could carry out a new cluster analysis using the three-hourly cloud fractions at different CTP irrespective of optical thickness provided in the ISCCP dataset. The two main disadvantages of this method are that the resulting cluster centroids are not robust and, more importantly, that it leads to a lack of a connection to the original regimes for which we have substantial knowledge. A second option is to use the original two-dimensional CTP-τ regime centroids and average over the τ dimension to yield new regime centroids that contain cloud fraction as a function of CTP only. The main disadvantage of this method is that regime centroids derived in this way possess a "visible adjustment" [*Rossow and Schiffer*, 1999], a correction of retrieved CTP using τ to account for the leakage of radiation through thin clouds. As the IR-only CTP histograms do not contain such an adjustment, this assignment would lead to incorrect matches in situations where thin clouds are present. Further investigations into these methods can be found in the Supporting Information.

[8] The approach used here is to first assign each three-hourly daytime CTP-τ histogram to one of the original cloud regimes. Then, for each CTP-τ histogram, we find the corresponding IR-only CTP histogram. Finally, the average of all the CTP histograms within each regime constitutes the centroids of the IR-only regimes (Figure 1). Each three-hourly CTP histogram can then be matched to the IR-only regimes using the Euclidean distance as per the second step of the original method. The advantage of the technique proposed here is that the IR-only centroids have a direct connection to the original cloud regimes and yet do not contain any CTP adjustment based on visible information.

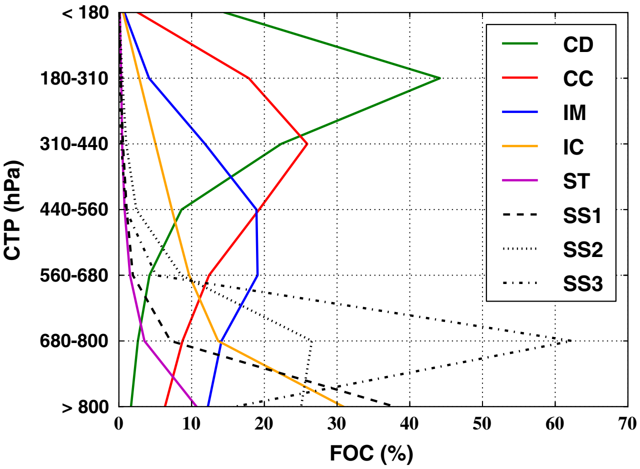

Figure 1. Centroids for the IR-only regimes, obtained by taking the mean CTP profile of the original regimes during daytime. The CD, CC, IM and IC regimes were introduced in the text; ST and SS represent suppressed regimes dominated by trade cumulus and stratocumulus clouds, respectively. The legend box presents the regimes in the order of descending convective strength.

[9] The most problematic regime to reproduce in the IR-only framework is a regime dominated by thin cirrus clouds (IC in (*Tan et al.*, accepted manuscript, 2013); WS4 in [*Rossow et al.*, 2005]), which shows a very high occurrence of thin cirrus clouds with CTP < 180 hPa and τ < 1.3. Yet, its IR-only centroid indicates an abundance of low clouds with nearly no high-topped clouds (Figures 1 and S2 in the Supporting Information). As discussed earlier, this discrepancy is due to the "visible adjustment" process in the ISCCP algorithm. As there is no simple way of replicating this correction without visible information, we choose to discard the IR-only centroid representing this thin cirrus regime (this regime occurs about 10% of the time in the original daytime-averaged regimes) and use only seven centroids. As a result, all instances for which the CTP-τ histogram would be assigned to the thin cirrus regime will now be assigned to the nearest of the seven remaining IR-only regimes.

[10] In the following section, we will evaluate the utility of the IR-only regimes by first assessing how well they replicate the original regimes during daytime only. We then test their usefulness by applying the new regime identification to two important convectively coupled phenomena, namely the MJO and the diurnal cycle of convection over tropical land.

3. Evaluation and Application

3.1. Comparison to Original Regimes

[11] Two-dimensional CTP-τ histograms in the ISCCP D1 dataset exist every three hours during daytime. Hence three-hourly assignment of the original regimes is possible during the sunlit hours and enables the comparison of the IR-only regimes against those derived using the full CTP-τ information. Figure 2 shows a matrix plot of how the IR-only regimes assignment compares to the original regimes. In this figure, the regimes have been sorted by "convective strength" as identified in (*Tan et al.*, accepted manuscript, 2013), from most active (CD) to most suppressed (SS3). The most striking feature in Figure 2 is that most of the cases

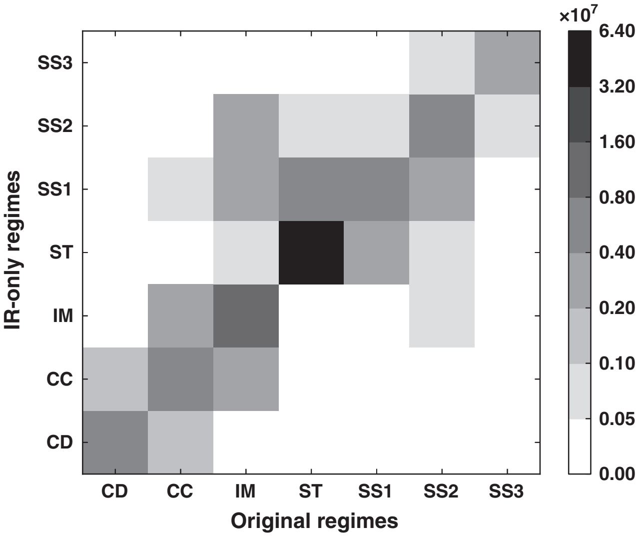

Figure 2. A matrix plot depicting how the IR-only regime assignment compares to the original regimes during daytime between 1984 to 2007. The original regimes are recreated based on seven centroids instead of the original eight. Note the geometric scaling of the color bar.

lie on or in the vicinity of the diagonal. The highest values are on the diagonal, which in total accounts for 66% of the cases. The implication is that each of the IR-only regimes captures the "correct" regime more often than any other "incorrect" regime, and that even when it is placed into a different regime, it still mostly falls into one of adjacent convective strength. This is especially true for the CD regime, a regime associated with the most intense convection and highest precipitation, with an exact match 78.3% of the time and in the neighboring CC regime 21.2% of the time, leaving only 0.5% of the cases assigned to weaker regimes.

[12] It is worth recalling that the IR-only regimes are constructed using a data set with only one-sixth the amount of information compared to the original regimes, so expecting perfect fidelity would be unrealistic. This is for instance true in the case of the CD and CC regimes, in which a sharp distinction between the two can easily be drawn in τ but not in CTP. Note that the loss of information in the τ dimension must naturally lead to mismatches (offset by a gain in temporal resolution), so the key question is not the degree to which the new regimes are matching the original ones, but whether they retain key information on the structure of tropical convection. We test this in the following section by applying the IR-only regimes to two convective phenomena and assessing if they are still good descriptors of the tropical convective atmosphere. A further investigation on the geographical distributions of the regimes can be found in the Supporting Information (Figure S4). To simplify our analysis, we interpolate the regimes from the original equal-area ISCCP grid to a 2.5° by 2.5° regular latitude-longitude grid based on the nearest neighbor technique.

3.2. Madden-Julian Oscillation

[13] The Madden-Julian Oscillation (MJO) is an intraseasonal mode of tropical variability manifesting as an eastward propagating band of convection [*Madden and Julian*, 1971]. In the equatorial Indian ocean, strong MJO events are easily noticeable by an eastward moving band of deep convective clouds preceded by shallower convection [*Kiladis et al.*, 2005]. Using the original regimes, *Chen and Del Genio* [2008] and *Tromeur and Rossow* [2010] discovered a peak in the occurrence of the CD regime and a minimum in the IM regime during the active phase of an MJO event.

[14] To illustrate the ability of the IR-only regimes in depicting the MJO, Figure 3a shows a time-longitude Hovmöller diagram of the frequency of occurrence (FOC) of the CD regime between 5°S and 5°N (4 grid boxes) from mid-December 2006 to mid-January 2007. The deep convective propagating core of the MJO is readily evident and is accompanied by an absence of the IM regime and a decline of the CC regime within two to three days of the strong CD signal (not shown).

[15] To elucidate the connections between the three different convective states represented by the CD, CC and IM regimes, we indicate in Figure 3b the dominant convective state at each time-longitude point by finding the most frequent regime in the same 10° latitude band (four grid points). The most salient feature of Figure 3b is the prevalence of weaker convective regimes before and after the main CD thread of the MJO, lending credence to the connection of these three regimes to the Stretched Building Blocks of convection. Contrasting this with the equivalent plot using the original daily regimes (Figure 3c), the transitions between the regimes are clearer and reveal changes at shorter timescales. In addition, westward propagating convective signals recognizable as 2 day waves [*Takayabu et al.*, 1996] can be identified in Figure 3a. These 2 day waves have a propagation speed of five to six grid boxes a day so they are also not visible in the daily regimes.

[16] We conclude that the IR-only regimes are useful indicators of different convective stages of the MJO and reveals more details than the original daytime-only regimes.

3.3. Diurnal Cycle

[17] A systematic error persistent in many models is the diurnal cycle of precipitation, which has been shown to be closely related to the representation of convection [*Yang and Slingo*, 2001; *Tian et al.*, 2004]. The original ISCCP-based regimes, despite being good proxies of convection on the large-scale, cannot be used in studying the diurnal cycle of convection due to the absence of the nighttime information. The IR-only regimes can, in principle, overcome this shortcoming.

[18] We analyze the utility of the IR-only regimes by studying the average FOC of the regimes at each 3 hour time period over tropical South America (20°S–0°, 40°W–70°W) for December-January-February in all years (1984–2008). Figure 4 shows the FOC for the IR-only regimes (solid lines) as well as the FOC of the original regimes during daytime (dashed lines) as a function of local time. The FOC of the IR-only CD regime is at a minimum early in the daytime, increases rapidly after noon to a maximum just before nightfall, and then decreases through the night. Not only does this match the original CD regime (dashed line), it also agrees with our expectations of continental convective behavior over the tropics: the build-up of convective clouds over the course of sunlit hours to the result of late afternoon precipitation [*Yang and Slingo*, 2001].

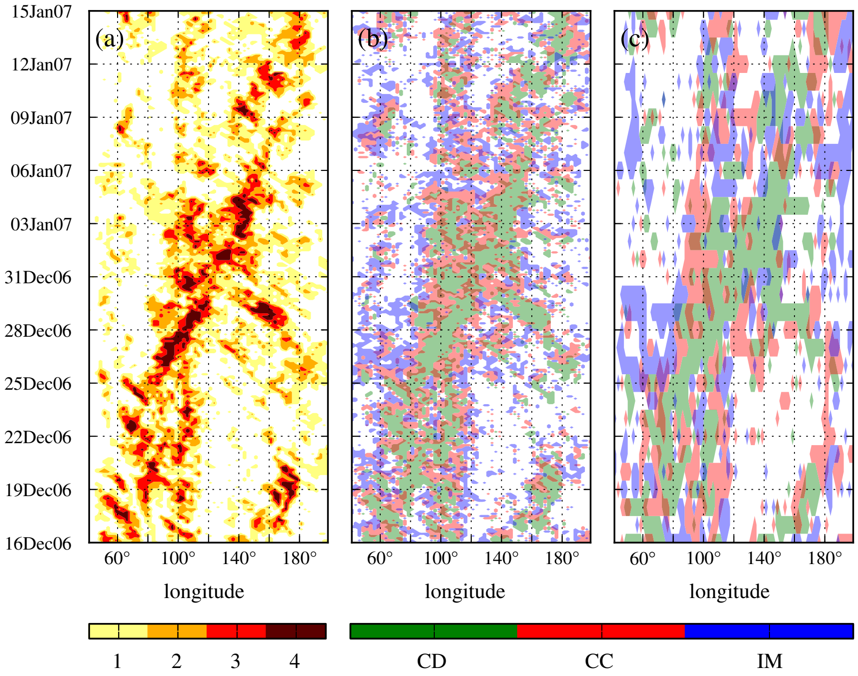

Figure 3. (a) The frequency of occurrence (FOC) of the CD regime between 5°S and 5°N (four grid boxes) expressed in a time-longitude diagram. (b) The regime which is dominant at each time-longitude, defined by a FOC of at least 2. Only the CD, CC and IM regimes are plotted. (c) Same as Figure 3b, but using daily regimes.

The IM regime, on the other hand, peaks at noon and appears to lead into the CD regime. This diurnal pattern concurs with both its mid-tropospheric CTP profile and its interpretation as congestus clouds in the original regimes. The CC regime is at its apex during nighttime, with a cycle that suggests a transition from the CD regime. This probably describes remnant cirrus from the deep stratiform clouds of the CD regime.

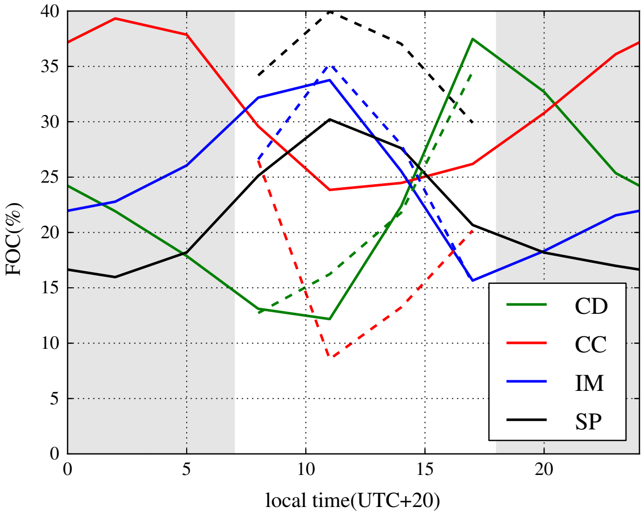

Figure 4. The average FOC of the regimes at each 3 h interval over the tropical South America (20°S–0°, 40°W–70°W) for December-January-February in all years. SP denotes suppressed regimes (all other than the stated three). The dashed lines are the original regimes.

[19] However, Figure 4 also exposes the differences of the IR-only from the original regimes. Using the original regimes at daytime, the CC regime is overestimated while the SP (suppressed) regimes are underestimated. An examination into the accuracy at each 3 h period in this domain shows that many cases which are SP in the original regimes are classified as IM in the IR-only case, and many cases which should be IM were identified as CC. The apparent agreement of the IM regime between the IR-only and original regimes in Figure 4 is therefore an accidental balance of misdiagnoses from CC and SP. Such overlap between regimes of neighboring convective strength is also reflected in Figure 2. The CD regime, conversely, does not show large differences and thus provides a reliable reflection of the diurnal behavior of organized deep convection.

4. Conclusion and Discussion

[20] In this study, we propose a new technique to extend ISCCP-based tropical cloud regimes, to three-hourly time resolution. The original daytime-only regimes describe recurring tropical cloud distributions and are empirical indicators of various stages of convection, so an extension in time resolution allows a more detailed examination of convective processes and associated larger scale phenomena. A comparison with the original regimes during daytime show that the new IR-only regimes match those based on more information most of the time, and even when they do not, they often fall into adjacent regimes of convective strength.

[21] An application to an MJO event showed that the new regimes displayed a very distinct progression from shallower convective regimes (CC and IM) to the strongly convective regime dominated by deep stratiform clouds (CD). They identified transitions in greater detail than in the original

regimes. Application of the IR-only regimes to the diurnal cycle over tropical South America showed promise. Both the strong convective (CD) and congestus (IM) regime showed peaks at the expected time of day. Comparisons with the original regimes in daytime revealed some erroneous compensation in regime assignments between the CC, IM and SP regimes.

[22] Given the long record of ISCCP with global coverage from 1983, the IR-only regimes derived here provide a substantial amount of information on the convective state of the atmosphere. They constitute an extension over the original regimes in time resolution and availability at night. As shown by (*Tan et al.*, accepted manuscript, 2013), it is likely that the CD, CC and IM regimes are empirical representations of the Stretched Building Blocks of tropical convection [*Mapes et al.*, 2006]. A three-hourly resolution through 24 h of the day allows the application of the rich cloud regime information to the study of the diurnal cycle of convection including a more in-depth analysis of its representation in models. In short, we consider the three-hourly IR-only cloud-regime data set derived here as a useful extension of the toolset in the study of the large-scale distribution and behavior of tropical convection. Studies using cloud regimes—including in regions outside the tropics—should consider applying the technique here to extend their time resolution. The data set can be downloaded at: http://mwac.its.monash.edu/mwac/pub/listPubCollections.jspx.

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