13C.5 THE LARGE-SCALE PROPERTIES OF TROPICAL CONVECTION

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1 INTRODUCTION

Tropical convection plays a major role in Earth's weather and climate, governing many meteorological phenomena such as the formation of clouds and distribution of precipitation. It is the primary mechanism for the transport of heat, momentum and moisture, not only from the local surface to the troposphere, but also horizontally through large-scale circulations such as the Hadley cells.

Despite its importance, the representation of convection in general circulation models (GCMs) has many deficiencies, as evident from the significant biases in clouds and precipitation (Soden and Held, 2006; Bauer et al., 2011), as well as the poor simulation of tropical intraseasonal variability (Lin et al., 2006). Due to the coarse resolution of most models, convection must be represented by parametrisations. One of the key assumptions in most of these parametrisations is that convection in a grid box can be represented diagnostically, i.e., without regard for spatial and temporal organisation beyond a single grid box and the current timestep. Thus, it is assumed that spatial and temporal connections can be made through the resolved equations alone, an assumption that has not been rigorously tested. Our long-term goal is to provide a framework to test this assumption in large-scale models. Doing so requires knowledge of the organisation of convection beyond the scale of a single GCM grid box. The aim of this study is to present a new framework for the description of the large-scale organisation of convection.

As a proxy for convection, we use the objective cloud regimes first introduced by Jakob and Tselioudis (2003). These regimes are the results of a clustering algorithm applied to global cloud satellite data, describing repeating cloud patterns in the atmosphere. The purpose of this study is to show that the unique signatures of these cloud patterns provide a window into identifying the state of convection in an area comparable to a GCM grid box and to investigate how these convective states are related to the large-scale state of the atmosphere. This sets the scene for future investigations into the spatial and temporal characteristics of convection in relation to large-scale atmospheric conditions.

2 METHODS

Our investigation of tropical convection is performed using tropical cloud regimes (Jakob and Tselioudis, 2003). These cloud regimes are derived from the International Satellite Cloud Climatology Project (ISCCP) D1 dataset (Rossow and Schiffer, 1999), which provides joint-histograms of the frequency of occurrence of clouds with a certain combination of cloud top pressure (CTP) and optical thickness (τ) for 280 km $\times$ 280 km equal-area grids. Following the methods outlined in Rossow et al. (2005), we apply the k-means clustering algorithm (Anderberg, 1973) to daytime-averages of the joint-histograms between 35°N and 35°S between 1985 and 2007. Eight cloud regimes are uncovered (Fig. 1).

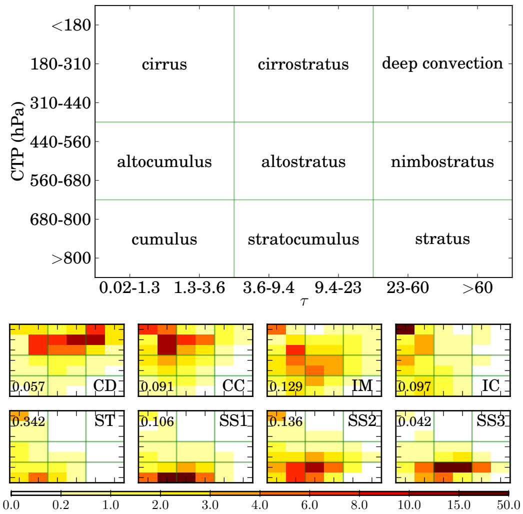

Figure 1: (Top) Cloud morphologies associated with the ISCCP joint-histogram (Rossow and Schiffer, 1999). (Bottom) Joint-histograms of the centroids of the eight regimes (see Table 1). Numbers indicate their relative frequencies of occurrence (FOC) over the ocean.

The eight regimes are identical to those found in Mekonnen and Rossow (2011) and Oreopoulos and Rossow (2011), and many of them match those identified in earlier studies that applied a similar analysis to different areas and time periods (see e.g. Jakob et al. (2005), Rossow et al. (2005) and Jakob and Schumacher (2008)). This strongly suggests that these regimes are robust features in the cloud fields.

As the eight regimes describe recurring cloud patterns in the tropics and subtropics, they potentially enable the distinction of convectively-active and convectively-suppressed states of the atmosphere. This is indicated by, respectively, the presence or absence of optically-

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thick high-top clouds. Based on the joint-histograms depicted in Fig. 1, we label the cloud regimes according to their convective character (convective, intermediate or suppressed) and dominant cloud type (see Table 1).

	dominant cloud type	
Convective:	**D**eep stratiform (**CD**)	**C**irrus (**CC**)
Intermediate:	**M**ixture (**IM**)	thin **C**irrus (**IC**)
Suppressed:	**T**rade cumulus (**ST**)	**S**tratocu. (**SS1-3**)

Table 1: Names and abbreviations of the eight regimes based on convective strength and dominant cloud type.

The main goals of our analysis is to establish if the ISCCP-based cloud regimes provide insights into states of tropical convection and how they are related to the large-scale atmospheric state. To do so, we interpolate the regime field to a 2.5° $\times$ 2.5° grid using the nearest-neighbour technique and then composite selected atmospheric variables by regime. The variables we present here are: daily precipitation from the Global Precipitation Climatology Project (Adler et al., 2003); outgoing longwave radiation at top of atmosphere from the ISCCP Flux Data (Zhang et al., 2004); saturation ratio (Bretherton et al., 2004), lower tropospheric stability (Klein and Hartmann, 1993) and vertical velocity at 600 hPa, all derived from the ECMWF Re-Analysis (ERA-Interim) data (Dee et al., 2011). Saturation ratio is ratio of the column-integrated specific humidity to the column-integrated saturation specific humidity, and lower tropospheric stability is the difference in potential temperature between 700 hPa and the surface.

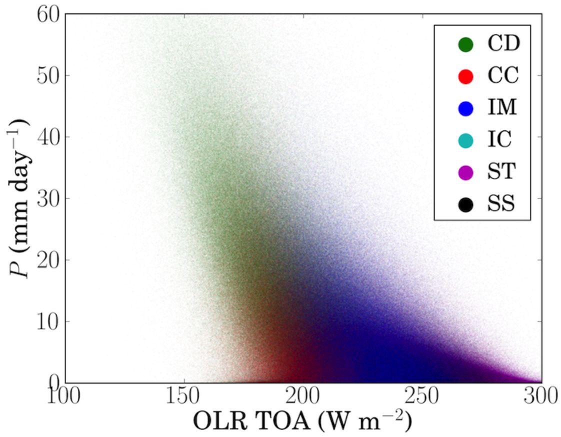
Due to orographic artefacts in the regimes associated with the use of pressure as the vertical coordinate in ISCCP, we restrict our analysis to only oceans. In addition, since our focus is on convection, we henceforth combine the three stratocumulus regimes into a single regime.

3 RESULTS

3.1 Convective Strength of Regimes

Two frequently used measures of convective strength are outgoing longwave radiation at the top of atmosphere (OLR TOA) and precipitation. A low OLR TOA and high precipitation are indicators of an atmosphere with strong convection.

Fig. 2 (top) shows the composites of OLR TOA and daily precipitation P with the regimes. Generally, convective regimes occupy the left portion of the diagram while suppressed regimes populate the tail on the right, and intermediate regimes are located between the two. This lends some credibility to our classification of convective, intermediate and suppressed regimes. Note that the SS regimes are hardly visible because of their low P values. The highest P and lowest OLR TOA are associated with the CD regime, followed by the CC regime. The mean P decreases and mean OLR TOA increases as we proceed through the intermediate regimes to the suppressed regimes. It is interesting to observe an upper limit for P as an inverse function of OLR TOA, which underlines a connection between these two variables through convective cloud processes.



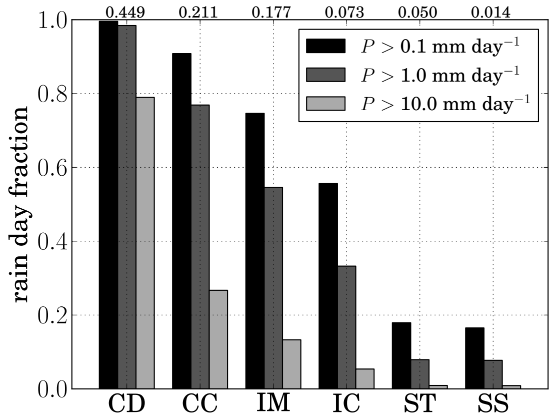


Figure 2: (Top) Composites of OLR TOA and P with regimes, presented in a scatter diagram. (Bottom) Fraction of days with rain above certain thresholds. Values at the top denote the fractional contribution of the regime to total precipitation.

The relationship between cloud regime and rainfall is further illustrated in Fig. 2 (bottom), which shows the fraction of days with P above certain thresholds. We exclude $P < 0.1$ mm day^{-1} to ignore cases with little precipitation. As expected, CD is associated with the largest occurrences of precipitation, with nearly all days having at least light rainfall (0.1 mm day^{-1}) and close to 80% with heavy rainfall ($>$ 10 mm day^{-1}). Jakob and Schumacher (2008) have identified this regime with a major contribution from stratiform precipitation. It is worth noting that this regime represents 45% of all precipitation even though it occurs only 5.7% of the time. In contrast, the other regimes including CC have relatively infrequent events of heavy precipitation. Nevertheless, these regimes are not devoid of precipitation; even the suppressed regimes ST and SS, which are primarily trade cumulus and stratocumulus respectively, are associated with occasional light rainfall.

These results suggest that the regimes exhibit a discrete spectrum of convective strengths, progressing from the very strong CD regime to the weak suppressed regimes. This reinforces our case for using them as a proxy for convection. In particular, we conjecture that the CD regime represents strong convection with large stratiform clouds and rainfall, while the CC regime is more typical of deep convection without significant stratiform components. The IM regime is a transitional regime from suppressed to active conditions, while the IC regime is likely characterised by remnant cirrus with little active convection.

3.2 Large-Scale Environment of Regimes

Having established the usefulness of the cloud regimes to describe convection, we now investigate their relation to key large-scale atmospheric variables. Fig. 3 shows the composites of lower tropospheric stability LTS, vertical velocity ω and saturation ratio r for each of the six regimes. A low LTS (unstable), strongly-negative ω (ascending) and high r (wet) is typical of a strong convective environment. Indeed, the CD regime fulfils these attributes, with a spread of points in the plot axes that is distinctive from all other regimes. The CC and intermediate regimes show a progression to drier and more stable large-scale conditions with more moderated upward vertical motion. The suppressed regimes, on the other hand, generally inhabit dry environments with large-scale descending motion and a prevalence of high values of LTS, especially in the SS regime.

Fig. 3 shows a wide scatter of points for all regimes. This is at least partly an artefact of the plotting technique, which cannot account for the actual density of points. To provide further insight into the regime characteristics, the crosses and values on the colour bar indicate the quartiles of the three variables. It is evident that the interquartile ranges, comprising 50% of the values, for each of the regimes fall into a relatively narrow band of large-scale states. In light of this, the apparent overlap between each regime in the parameter space is in fact not as large.

All in all, the convective regimes are wet, unstable and mostly exist in ascending motion, while the suppressed regimes are dry, stable and mostly exist in descending motion. Intermediate regimes, on the other hand, straddle these two extremes.

4 DISCUSSION

In the previous section, we have used two conventional measure of convection, outgoing longwave radiation at top of atmosphere and precipitation, to show that the regimes defined based on ISCCP cloud information serve as a useful indicator for convective strength. The large-scale variables associated with them also demonstrate distinguishable atmospheric conditions that the regimes occur in. It is worth remembering that the regimes are statistically derived from cloud properties alone, independent of any assumptions about the underlying physics of the environment. Hence we conclude that the regimes can be interpreted as empirical archetypes of the convective state of the atmosphere.

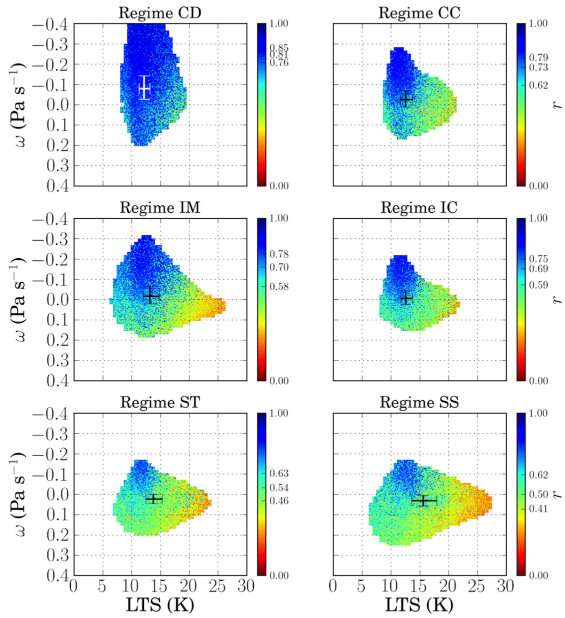


Figure 3: Scatter diagram of the relationship between lower tropospheric stability (x-axis), vertical velocity (y-axis) and saturation ratio (colour) for each regime. Quartile values are indicated by the crosses and colourbar ticks. Points lying outside the 0.95 contour of the density of points are discarded.

Our results quantify the CD regime as a wet, thermodynamically unstable and heavily precipitating regime with large-scale ascending motions. This is consistent with its joint-histogram (Fig. 1, bottom), which reveals a prevalence of thick stratiform clouds. Its geographical distribution (not shown) shows a high frequency of occurrence in the Intertropical Convergence Zone and Tropical West Pacific region. With its 45% contribution to tropical precipitation, these facts imply that this regime can be associated with mesoscale convective complexes.

The CC regime is an archetype of a regime of less organised deep convection, as it displays weaker precipitation, a drier environment and a prevalence of thin cirrus. The IM regime shows a mixture of coexisting cloud types including some coverage with mid-level top congestus and altocumulus or altostratus clouds. Together, the CD, CC and IM regimes can be interpreted as the three "building blocks" of precipitating tropical convection, namely shallow congestus convection (IM), deep precipitating convection (CC) and regions with strong stratiform cloud influence (CD).

We have shown that the regimes show reasonably strong relationships to the large-scale state of the atmosphere, making them a potential tool to investigate the nature of these relationships, which are at the heart of the cumulus parametrisation problem.

5 CONCLUSION

We have used tropical cloud regimes derived by applying cluster analysis to the ISCCP D1 dataset to investigate the large-scale properties of tropical convection. The regimes represent recurring cloud patterns on the scale of 280 km $\times$ 280 km, and their composites with outgoing longwave radiation at top of atmosphere and daily precipitation show that they depict states of different convective strength. Composites with selected large-scale variables relate convective regimes with wet, unstable and ascending environments, suppressed regimes with dry, stable and descending environments, and intermediate regimes with transitional large-scale states.

There are numerous potential applications for our results. First, we can perform a similar analysis in a climate model and investigate if the model accurately reproduces not only the regimes themselves, but also their association to the larger scales. Second, we can use our composites as a basis for a stochastic model of tropical convection which takes into account the large-scale environment. Such a computationally-efficient model may complement current parameterisation schemes by providing information about the state of convection beyond a single model grid box and timestep, as is the current situation in GCMs.

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