Tropical climate described as a distribution of weather states indicated by distinct mesoscale cloud property mixtures

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[1] An analysis approach that uses the patterns of cloud property joint distributions at mesoscale (cloud type mixtures) from the International Satellite Cloud Climatology Project to identify distinct weather states of the tropical atmosphere is extended to the whole tropics covering the period 1983–2004. These patterns can be used as the basis for multi-scale, multi-variate compositing of other observations to understand how tropical cloud systems affect the atmospheric diabatic heating and interact with the large scale circulation. We illustrate how variations of the tropical climate on longer time scales can be described in terms of the changes in the frequency of occurrence of these weather states with their associated multi-variate relationships. **Citation:** Rossow, W. B., G. Tselioudis, A. Polak, and C. Jakob (2005), Tropical climate described as a distribution of weather states indicated by distinct mesoscale cloud property mixtures, *Geophys. Res. Lett.*, *32*, L21812, doi:10.1029/2005GL024584.

1. Motivation

[2] Difficulties in understanding the tropical atmospheric circulation and its part in climate variations arise from the fact that the large-scale oceanic circulation is coupled to the large-scale atmospheric circulation via small-scale convective processes [*Webster*, 1994]. The multi-scale exchanges of energy and water comprising tropical weather are described by the interaction of a large number of variables that are all coupled by cloud processes and that are difficult to observe and model over the whole range of scales. One way to attack this problem is to simplify these complex relationships and variations by looking for a small number of distinct weather patterns that associate particular cloud properties with particular atmospheric motions [cf. *Mo and Ghil*, 1987, 1988; *Zivkovic and Louis*, 1992; *Kimoto and Ghil*, 1993; *Palmer* 1998]. In the tropics, a direct combination of meteorology (winds and/or surface pressure) and cloud/radiation/precipitation observations, similar to the compositing approach used by *Tselioudis et al.* [2000] in midlatitudes, is suspect because the available wind/pressure measurements are so sparse and lacking in detail about the divergent component of the circulation that the consequent weather analyses (and reanalyses) of the circulation are much more sensitive to model parameterizations (but see *Del Genio and Kovari* [2002] and *Bony et al.* [2004]). In this paper we extend to the whole tropics the analysis approach of *Jakob and Tselioudis* [2003, hereinafter referred to as JT03] that uses the patterns of cloud property joint distributions at mesoscale (cloud type mixtures) to identify distinct states of the tropical atmosphere. We suggest that these patterns can be used as the basis for multi-scale, multi-variate compositing of other observations to understand how tropical weather events affect the atmospheric diabatic heating. Further, variations of the tropical climate (longer time scales) can then be described, not in terms of the averages of variables, but in terms of the changes in the frequency of occurrence of these weather states with their associated multi-variate relationships. For instance, if distinct values of the diabatic heating of the atmosphere by radiation, precipitation and surface fluxes can be associated with these states of the tropical atmosphere, then a quantitative estimate of climate feedback by the whole set of processes is possible [cf. *Tselioudis et al.*, 2000; G. Tselioudis and W. B. Rossow, Climate feedback implied by observed radiation and precipitation changes with midlatitude storm strength and frequency, submitted to *Geophysical Research Letters*, 2005]. This approach could provide a more compact way to study multi-variate relationships.

2. Data and Analysis Method

[3] As suggested by *Rossow and Schiffer* [1991] and following JT03, we look for distinctive patterns in the joint frequency distributions of the cloud top pressure (PC) and optical thickness (TAU) values from individual satellite image pixels (fields-of-view about 5 km in size) occurring within 2.5° regions (upper limit of the mesoscale) that are provided in the International Satellite Cloud Climatology (ISCCP) D1 dataset [*Rossow and Schiffer*, 1999]. We will also refer to specific combinations PC-TAU by the cloud type names defined in *Rossow and Schiffer* [1999]. We extend the results of JT03 to the whole tropics (±15° latitude) covering 21.5 years (1983–2004).

[4] The histogram patterns that describe cloud variability are identified using the K-Means clustering algorithm [*Anderberg*, 1973] applied to 3-hourly PC-TAU histograms for each 2.5° region, including completely clear regions. This algorithm iteratively searches for an optimum set of a predefined number (K) of cluster centroids (representing specific histogram patterns) by assigning each PC-TAU histogram to the cluster with the nearest centroid (as measured by a Euclidian distance of similarity), i.e., each histogram is assigned to the cluster whose centroid histogram pattern is most similar to it. The initial K cluster

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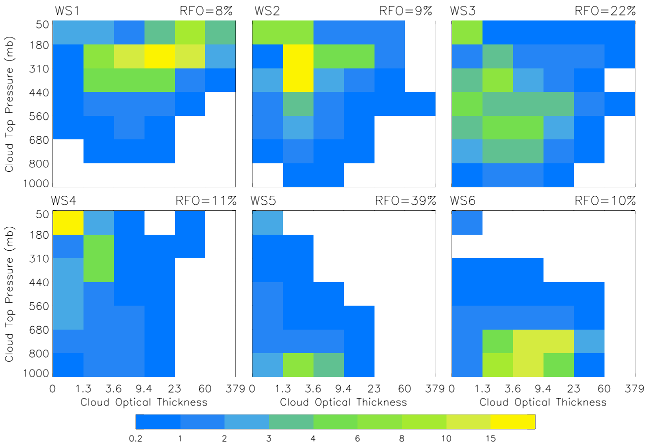

Figure 1. The six cloud top pressure (PC) – optical thickness (TAU) frequency histogram patterns (called weather states, WS) that best describe the 3-hourly variations of cloud properties in 2.5° latitude-longitude regions covering the whole tropics (±15° latitude) for 21.5 years (1983–2004) from ISCCP data. The states are numbered (upper left corner) from "most convectively active" to "least convectively active" and their relative frequencies of occurrence (RFO) are shown in the upper right corner.

centroids are selected at random. After all histograms are assigned to one of the clusters, new centroids are determined and used as the new seed points for re-calculating the distances. Other distance measures were tried but they did not alter the results significantly. The optimum cluster set is obtained when the sum of all the distances between individual histograms and the centroids is a minimum. Thirty iterations were performed to insure convergence but usually it was obtained in less than ten iterations.

[5] Unlike JT03, the "best" number of clusters is determined objectively by repeating the analysis for an increasing number of clusters (starting at four, since JT03 tested 2–4 clusters) and judging the outcome by four criteria: (1) the resulting centroid histogram patterns must not change significantly (as judged by the pattern correlations among the centroids) when the random number initiating the analysis or the subset of data analyzed is changed, (2) the resulting centroid patterns should differ from each other significantly (pattern correlations should be low, usually <0.6), (3) the spatial-temporal correlations of the centroid histograms should also be low, and (4) the distance between cluster centroids should be larger than the dispersions of the cluster member distances from the centroid. Tests showed that the results were unstable (violation of the first criterion) when the cluster number was too small (K < 6 in this case) and that, when the cluster number was increased, the patterns of the new clusters were still significantly different from each other (second criterion). When there were too many clusters (K > 6), two or more of them had very highly correlated PC-TAU patterns, as well as highly correlated spatial distributions or time variability (usually all three). In particular, two of the K-cluster patterns are highly correlated with a single cluster pattern from the (K-1) analysis, indicating a splitting of that cluster. The last criterion is actually used in the analysis to optimize the cluster set, so it is always met; but a post-facto check showed generally decreasing dispersion-to-separation distance ratios as the number of clusters increases. For K = 6 the average dispersion-to-separation distance ratio is less than one half.

[6] Once the optimum cluster centroids are identified, each PC-TAU histogram for each 3-hr time step in each 2.5° map grid cell over the whole tropics is assigned to one of these clusters. We refer to these as "weather states" (WS) because JT03 showed that these cloud property patterns are associated with distinct states of the tropical atmosphere [see also *Fu et al.*, 1990, 1994; *Lau and Crane*, 1995; *Del Genio and Kovari*, 2002]. Variations of WS can then be represented by the frequency of occurrence maps for daily or longer time accumulations. To examine the time variations of the WS frequencies of occurrence, we used a wavelet (Morlet mother wave [*Torrence and Compo*, 1998]) analysis.

3. Weather States Describing the Tropical Climate

[7] The mesoscale distributions of cloud top pressure and optical thickness in the tropics are well represented by the six patterns (weather states, WS) shown in Figure 1. Despite some changes in methodology and a substantial change in the domain, four of the WS are the same (pattern correlation >0.8) as found by JT03 for the western Pacific: WS1 is #4, WS2 is #2, WS4 is #3 and WS5 is #1 in JT03, respectively. The two additional states (WS3 and WS6) represent situations not found frequently in the western Pacific. As shown by the frequency of occurrence maps for each WS in Figure 2, WS3 is found predominantly over land areas, especially over high topography (note east central Africa), but also occurs in the oceanic ITCZ outside of the western Pacific area. WS6 is the subtropical marine stratus regime off the west coasts of South America and Africa (the corresponding regimes in the northern hemisphere are located at higher latitudes).

[8] Based on JT03 and further comparisons of the weather states with meteorological data of *Jakob et al.* [2005] and us (not shown) that show the expected correspondence of convective activity with vertical motions and atmospheric moist static energy profiles, we can

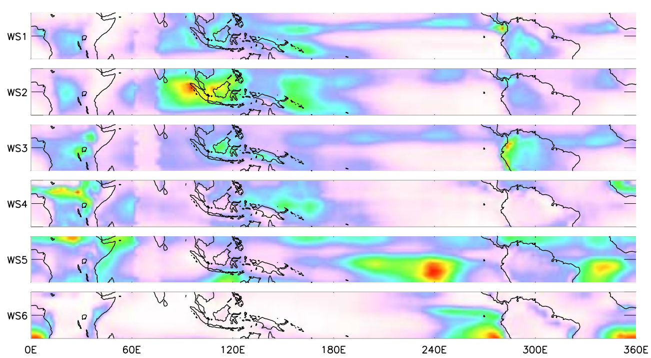

Figure 2. Maps showing the frequency of occurrence of each of the six tropical weather states as the fraction of the 3-hr time steps over 21.5 years (1983–2004) that are classified in each state.

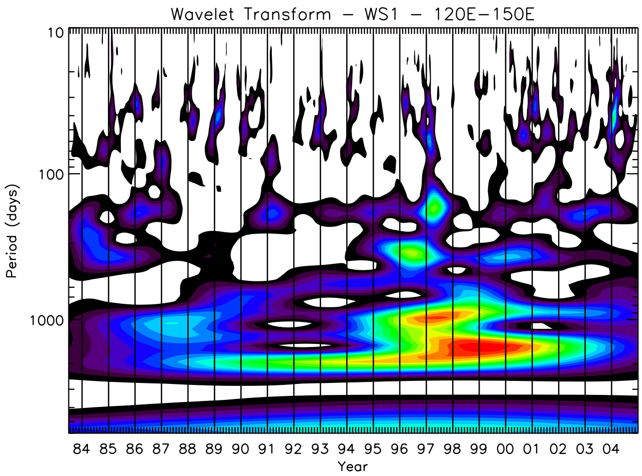

Figure 3. Wavelet analysis results showing the time dominant time scales of variation as a function of the year for WS1 in the western Pacific sector (120°E–150°E).

characterize the first three WS as "convectively active" (where "convective" refers to deep convection): WS1 is the most vigorous deep convection associated with the larger mesoscale systems (large amounts of deep convective and cirrostratus clouds), WS2 is less vigorous (less deep convective and cirrostratus clouds) but exhibits more thick cirrus, and the additional state (WS3) exhibits somewhat lower cloud tops at medium optical thicknesses but also somewhat more deep convective clouds with very high tops, suggesting isolated, smaller-scale convective systems with tops at a range of altitudes [cf. *Machado and Rossow*, 1993; *Machado et al.*, 1998]. WS2 and WS3 include the cumulus congestus discussed by *Johnson et al.* [1999] as indicated by a mid-level-topped population with large optical thicknesses (Figure 1). We will refer to these three WS collectively as the "convectively active" states. The last three WS are "convectively inactive": WS4 is primarily thin cirrus that is either outflow from distant convection or generated in isolation by other atmospheric motions [cf. *Luo and Rossow*, 2004], WS5 is a mixture of trade and shallow cumulus with some thin cirrus and WS6 is the marine stratus. Especially notable in Figure 2 is the distinct transition from marine stratus (WS6) to scattered cumulus (WS5) as the distance from the west coast of the continents increases.

[9] The frequency distribution of the six WS over the whole tropics for the 21.5-yr period shows that the most frequent states are WS3 and WS5, indicating a predominance in the tropics of smaller-scale convective clouds with a range of tops and shallow boundary layer convection. The three "convectively active" states, together, account for a little less than 40% of the area and time, whereas the "inactive" states account for a little more than 60%. In other words, deep convective clouds (and associated heavy precipitation) are relatively rare events even in the tropics: deep convective activity is not the dominant state of the tropical atmosphere, rather shallow convection with cirrus is the dominant state.

[10] Figure 2 shows other notable features. In the western Pacific (120°–150°E), the region where the JT03 analysis was done, the convectively active states occur much more frequently than elsewhere in the tropics and WS4 (cirrus) is actually concentrated in between the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) or north and south of the ITCZ [cf. *Luo and Rossow*, 2004]. The distribution of WS in central Africa differs most from other parts of the tropics, exhibiting more frequent isolated cumulus and cumulus congestus, along with more cirrus and less frequent mesoscale convective systems.

[11] The frequency distributions of the WS can be used to determine transition probabilities among the states at different time scales. Consistent with the intermittancy of convection, we find that on a time scale of 1 day, convectively active states transition to or arise from convective states, whereas convectively inactive states transition to or arise from inactive states. On time scales as long as 15 days, the distribution of states preceding or following a particular state is just the climatological distribution, indicating that this time scale is generally long enough for all states to occur.

4. Time Scale Interactions

[12] To illustrate the use of the six-weather-state representation of tropical climate for an analysis of time variations, we show (Figure 3) the results of a wavelet analysis of the daily distributions of WS1 (vigorous deep convection) over the western Pacific sector (120°–150°E) to determine the dominate time periods of variability present at different times during the whole 21.5-yr record. The dominant signal consists of variations with periods from 1000–3000 days concentrated in the second half of the period; in the first half of the record, the variability is concentrated at 1000 days in the late 1980s. This complex pattern appears to reflect the variety of time scales associated with the ENSO events during these two decades, where there were more events in the 1990s than in the 1980s. Significant variability is also apparent at the annual time scale but the strength of this variability varies from year to year, being notably weak in 1987–1989 and 1992–1994 during (weak) ENSO events. The annual variability signature is much more important than the ENSO signature for the whole tropics as expected. The other convectively active states show more uniformity in their annual variations than WS1, suggesting year-to-year variations in the intensity and organization of convection.

[13] Also notable in Figure 3 is variability concentrated in the boreal winter-spring part of most years with periods from 30–60 days. The specific events indicated in Figure 3 correspond very well with the MJO index time record shown by *Wheeler and Hendon* [2004]. This MJO signature for WS1 is weaker over the Indian Ocean sector (not shown) and extends over longitudes from 60°E to 180°E. The MJO signature for WS1 is not apparent in all years, being notably absent in 1998–2000; but analysis of WS2 and WS3 (not shown) shows that the MJO signature is very intermittent, suggesting a very close association of organized convection with the MJO. Although there is a weak indication of intraseasonal variations at other longitudes in the tropics (with somewhat longer periods), variations are more concentrated at annual and very long (>5000 day) time periods.

[14] Of particular interest in all these results are indications of time-scale interactions as the dominant variability shifts from one period-band to another over the 21.5 years. In Figure 3 for instance, strong MJO signatures occur in the same years as ENSO signatures, whereas the annual variation is stronger in years with weaker MJO and ENSO variations. This feature deserves more extensive analysis.

5. Comments

[15] The general analysis approach that we have illustrated here makes possible many other interesting and potent studies of tropical meteorology and climate. By sorting other datasets describing atmospheric motions and the diabatic heating (radiation and precipitation) by their association with each of these distinct WS, we can examine how convective systems form, mature and decay, how they vary diurnally and synoptically, and how convection interacts with the larger-scale tropical circulation on longer time scales. Transition probabilities among the states can be examined as well as the statistics of which state(s) precede the formation of the larger mesoscale convective complexes. Composite analyses of convectively active states can be used to examine the relative importance of surface flux and large-scale convergence variations for triggering convection and whether this varies with location and time. The analysis illustrated in Figure 3 can be extended to a wavelength-frequency analysis, like that of *Wheeler and Kiladis* [1999], to examine the association of each weather state (convective activity) with different tropical waves. The long-term variability of tropical climate can be studied in terms of changes in the frequency of occurrence of the WS. Since many weather and climate GCMs have now implemented the ISCCP Simulator [*Klein and Jakob*, 1999] as a diagnostic of their model's cloud properties, this same cluster analysis can be applied to GCM representations of the tropical atmosphere for comparison with the results from ISCCP [*Jakob et al.*, 2005; *Williams et al.*, 2005]. To facilitate this, we have put our Cluster Analysis code and the 21.5-yr statistics illustrated here on-line at the ISCCP Web site [*Rossow and Duenas*, 2004; http://isccp.giss.nasa.gov] and the GCSS-DIME (Global Energy and Water Experiment Cloud System Study – Data Integration for Model Evaluation) Web site [*Tselioudis et al.*, 2004; http://gcss-dime.giss.nasa.gov].

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