How Representative are the Cloud Regimes at the TWP Sites? – An ISCCP Perspective

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Introduction

The Atmospheric Radiation Measurement (ARM) Program has established comprehensive cloud and radiation observatories in various locations across the globe with the aim of collecting measurements and developing models to better understand the processes that control solar and thermal infrared radiative transfer in clouds and at the surface. The locales of the individual ARM sites were chosen because they represent typical cloud regimes occurring in various climate regimes (Stokes and Schwartz 1994). However, little evidence has been provided so far of how typical the cloud regimes observed at the various sites are for the climate regimes in which they are embedded. This study aims to answer this question for the two facilities located at the ARM Tropical Western Pacific (TWP) site.

A useful data source for a study that aims to place cloud regimes at individual sites into a larger-scale picture are satellite observations of clouds. Here we use data provided by the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1983). The ISCCP dataset provides global information on a number of cloud parameters retrieved at three-hourly frequency from a combination of visible and infrared channels on both polar-orbiting and geostationary satellites. Among other products, the ISCCP D1 dataset used here provides joint histograms of the frequency of occurrence of clouds with a certain cloud top-pressure and optical thickness in grid boxes of ca. 280 x 280 km (Rossow and Schiffer 1991). An example for such a histogram is shown in Figure 1. Figure 1 shows the cloud top pressure-cloud optical thickness histogram averaged for one year (1999) over all grid boxes in a region located in the TWP (130° to 170°E, 10°N to 10°S) that includes the ARM TWP facilities. The strong relationship of the location of frequency of occurrence maxima in this diagram to prevailing cloud types is evident. For this tropical area we can identify a high frequency of cirrus, both transparent and opaque, located in the top left corner of the diagram as well as a fair number of occurrences of deep convective clouds with high optical thickness and high cloud tops (top right corner) as well as shallower, less optically thick clouds (bottom left part).

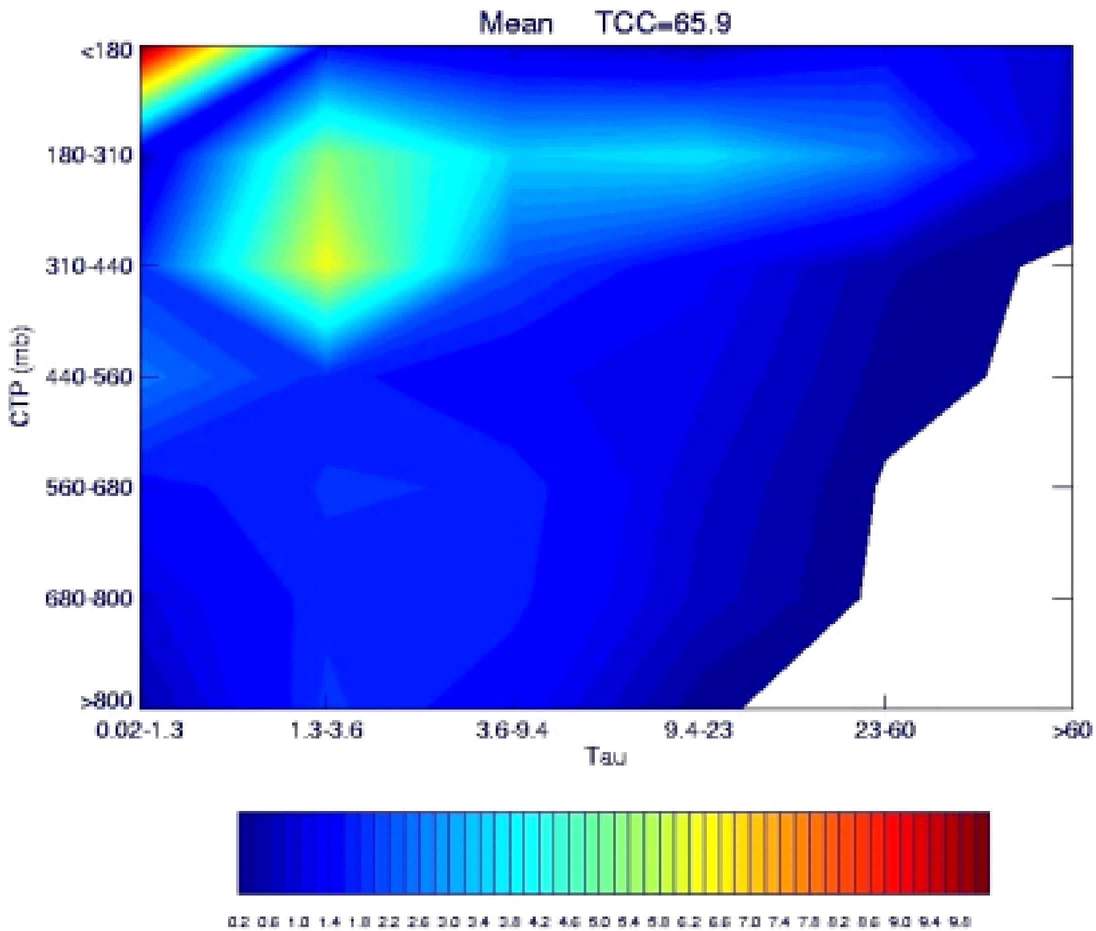

Figure 1. Mean CTP-τ histogram averaged for 1999 over all grid boxes in the TWP (130° to 170°E, 10°N to 10°S).

The link of these histograms to cloud types has been extensively used in recent studies to characterize different cloud regimes in both the ISCCP observations and general circulation models (e.g., Tselioudis et al. 2000; Webb et al. 2001; Norris and Weaver 2001; Tselioudis and Jakob 2002). These studies used various indicators such as surface pressure anomalies or vertical velocity to first identify "dynamical" regimes and then applied the ISCCP histograms to characterize the "response" of the cloud field to the large-scale conditions. Here we follow a different approach in attempting to statistically identify the prevailing "cloud regimes" in a certain region purely from the information contained in the ISCCP histograms themselves without any dynamical "preconditioning."

For this purpose we perform a cluster analysis on the dataset contained in Figure 1, i.e., a full year of histograms for the TWP region (ca. 160000 individual samples). We first investigate whether the statistically identified cloud regimes bear any resemblance to those we would intuitively expect to exist in the TWP based on physical reasoning. Then the cloud regimes identified over the entire TWP region will be used to put into context those encountered at the two ARM TWP site facilities at Manus and Nauru. This will provide crucial information on whether these sites can be deemed typical for the region and with what frequency the cloud regimes occurring over the entire region can be expected to be observed.

Typical Cloud Regimes in the Tropical Western Pacific

The basic question to address in identifying cloud regimes is whether the annually and spatially averaged cloud field in the TWP, as depicted in histogram form in Figure 1, is composed of a collection of random (in space and time) cloud situations or composed of cloud situations that can be grouped into recurring regimes. The statistical method we choose in addressing this question is cluster analysis. As its name suggests, cluster analysis searches for possible "clusters" in a collection of data, usually by evaluating a measure of distance between the individual data points. Note that in this case a "data point" is a vector with 42 elements comprised of the 42 classes in the ISCCP histogram. The particular clustering algorithm used here is that of KMEANS clustering (Anderberg 1973). This algorithm iteratively searches for a predefined number (k) of clusters using the following technique: (1) k elements of the dataset of size N are used as clusters of one member each. (2) Each remaining N-k element is assigned to the cluster with the nearest (in a Euclidian distance sense) centroid. After each assignment, the centroid of the gaining cluster is recalculated. (3) After all elements have been assigned, the centroids found in step 2 are used as new seed points, and the algorithm is iterated. In this study, a varying number of clusters is used while the number of iterations is held constant at ten.

The KMEANS algorithm is applied to all histograms in the TWP area defined above for the year 1999. Each of the histograms is treated as an independent data point, leading to about 160000 cloud situations entering the clustering. The key results of the analysis are the mean histogram within each cluster (cluster centroid), the number of cases within each cluster, which marks the frequency of occurrence of the identified cloud regime, and the total cloud cover (TCC) within each cluster, i.e., the integral over the entire frequency histogram. These parameters will be used below to describe the results of this study.

Given that the cluster algorithm allows for specification of the number of clusters to be searched for, it is logical to analyze the evolution of the results as this number is increased. Figure 2 shows the cluster means (centroids) identified when two clusters are searched for. The relative frequency of occurrence and (TCC) of each of the identified cloud regimes is indicated at the top of each panel. It is noteworthy that even this most basic separation of the dataset into two parts already delivers results that are physically interpretable. The first cloud regime represents 69% of the samples and is characterized by mostly transparent cirrus and low thin clouds with very little evidence of deep convection being present. The mean TCC of the regime is just above 50%. The second regime has a TCC of almost 100% and is characterized by a significant number of deep convective pixels as well as a high frequency of high top clouds with medium and low optical thickness, most likely anvil, and cirrus outflow from convection. This regime represents 31% of the cases sampled. The separation achieved in the two clusters is well in line with our expectation of the presence of convectively active and suppressed conditions known to exist in the tropics.

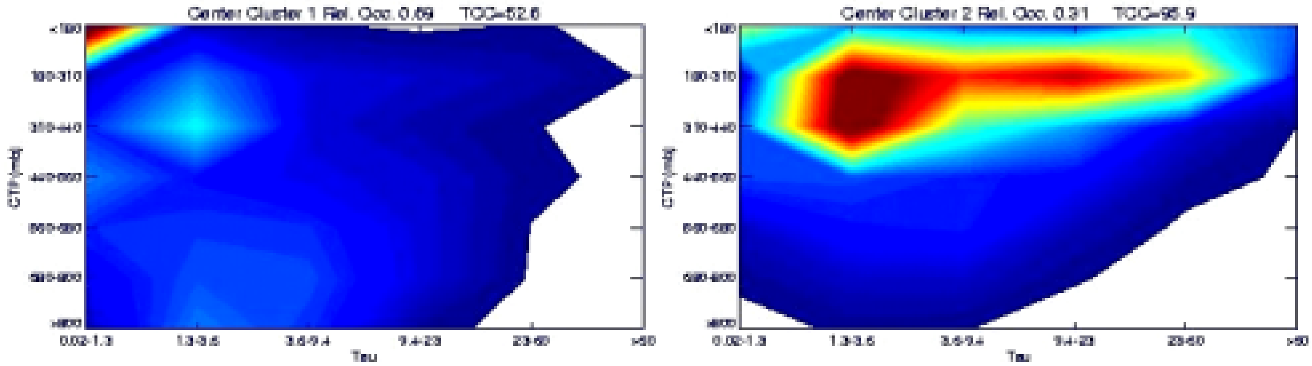

Figure 2. CTP -τ histograms of the centroids of a two-cluster analysis using all histograms for 1999 in the TWP (130° to 170°E, 10°N to 10°S).

Further division into more clusters leads to an interesting separation of those two basic cloud regimes into sub-regimes. Figure 3 shows the results for a four-cluster analysis. It is evident that the new clusters 1 (top left) and 3 (bottom left) result from a separation of cluster 1 in Figure 2, while clusters 2 (top right) and 4 (bottom right) are a result of splitting cluster 2 of the two-cluster analysis. This is confirmed by the three-cluster analysis (not shown), in which cluster 1 of the two-cluster analysis is split

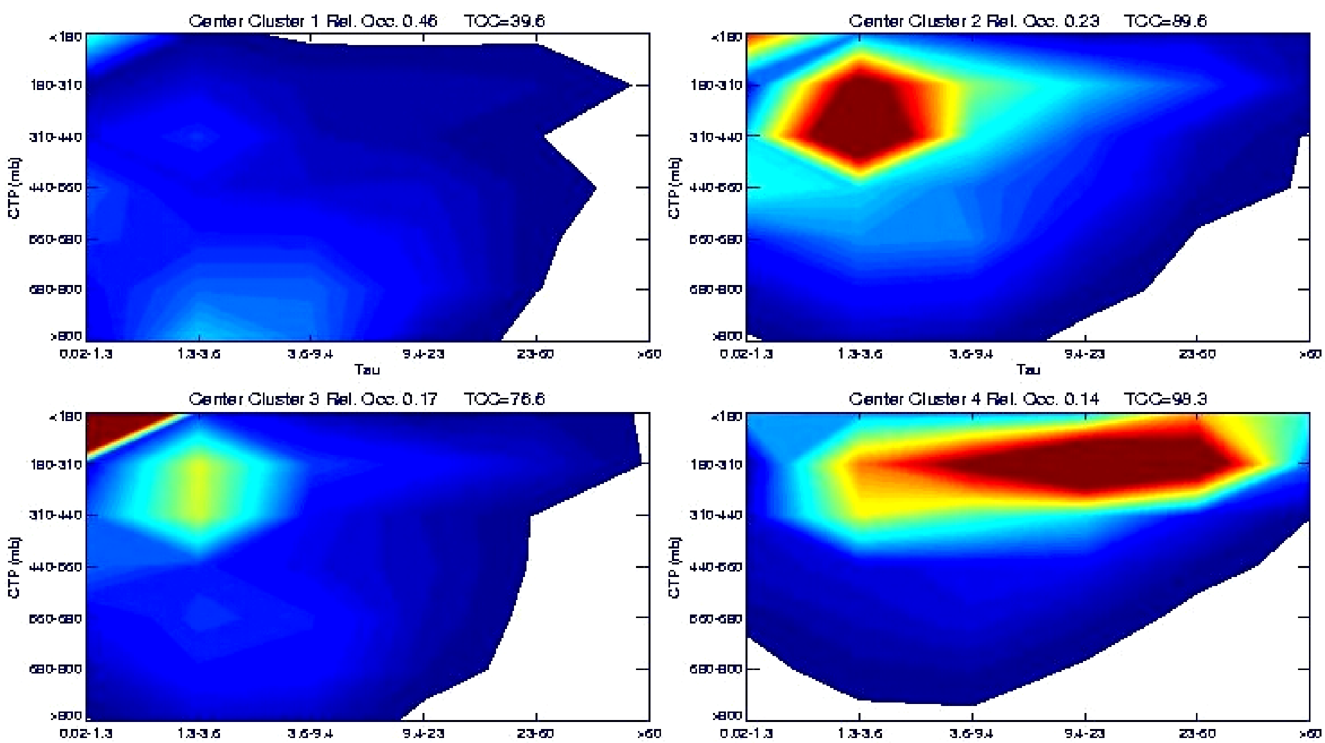

Figure 3. CTP-τ histograms of the centroids of a four-cluster analysis using all histograms for 1999 in the TWP (130° to 170°E, 10°N to 10°S).

while cluster 2 remains intact. It is worthwhile noting that each of these analyses is carried out independently using the full dataset, lending some credit to the robustness of the results. The cloud regimes identified in the four-cluster analysis are (1) a regime dominated by shallow clouds of medium optical thickness and low TCC (40%); (2) a high TCC (90%) regime dominated by cirrus of measurable optical thickness in the presence of some deep convection; (3) a regime dominated by transparent cirrus with little coincident deep convection and a TCC of about 75% and; (4) a strongly convective regime with a very high coverage with optically thick high-top clouds, most likely organized convective systems with significant stratiform anvil coverage, and a TCC of close to 100%. The four regimes occur in 46%, 23%, 17%, and 14% of the cases, respectively. Increasing the number of identified clusters to five (Figure 4) leads to a further subdivision of regime 2 identified above mainly by the location of the cloud tops with some small but not insignificant contribution from other clusters, with a regime of lower tops, including some thin clouds with tops near 500 hPa, emerging. Further increasing the number of clusters does not lead to the identification of significantly different regimes but rather focuses on some of the details within regimes and delivers clusters with very low population.

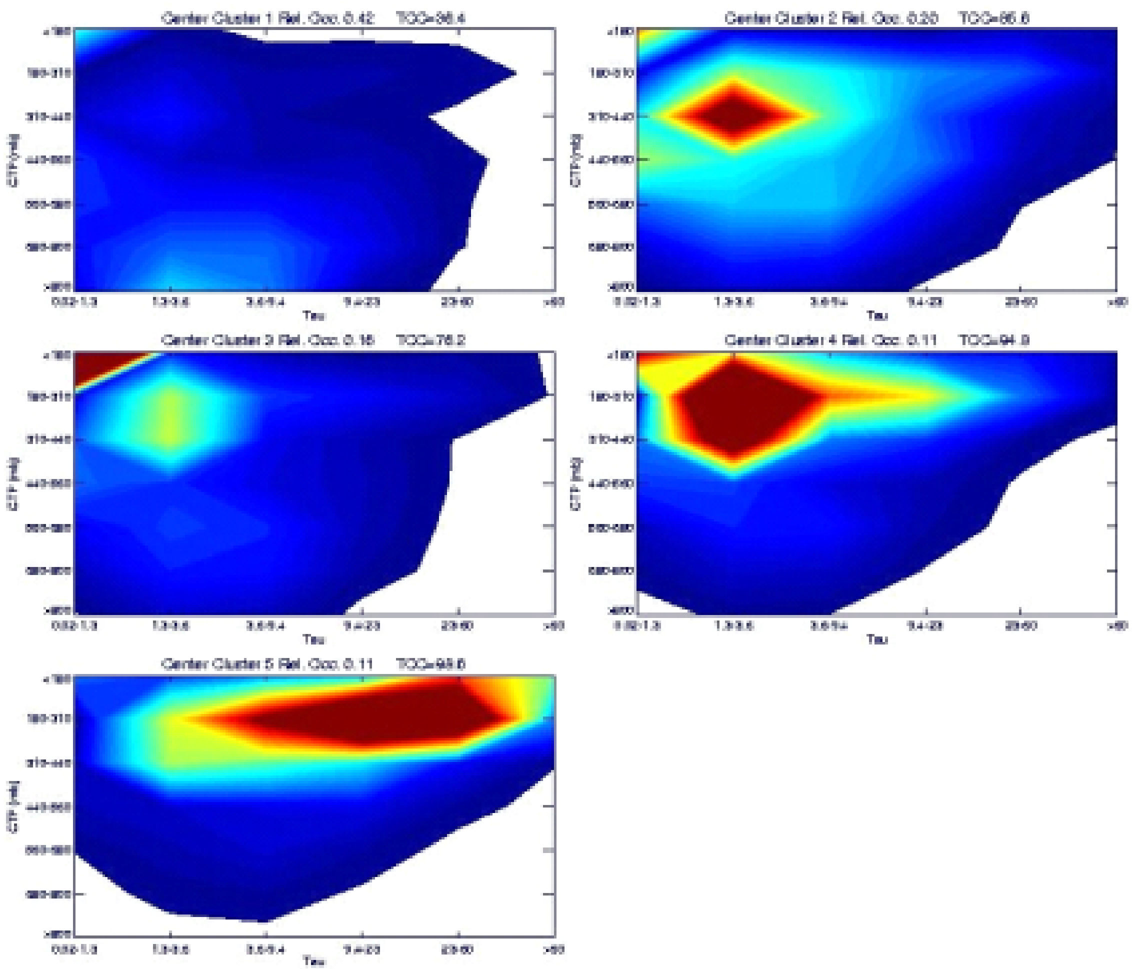

Figure 4. CTP-τ histograms of the centroids of a five-cluster analysis using all histograms for 1999 in the TWP (130° to 170°E, 10°N to 10°S).

In summary, we can conclude that for the TWP site, the cluster analysis method is able to provide physically interpretable cloud regimes. An optimum number of regimes for this dataset appears to be five. Following are the five regimes identified in order of their frequency of occurrence:

- Mainly shallow clouds – Frequency of occurrence: 42%, TCC = 36%
- Some deep convection and a dominance of mid-level top thin clouds – Frequency of occurrence: 20%, TCC = 86%
- Mostly transparent cirrus with no deep convection – Frequency of occurrence: 16%, TCC = 76%
- A convective regime with large amounts of high level cirrus – Frequency of occurrence: 11%, TCC = 95%
- Large amounts of deep high top clouds suggestive for large organized convective systems – Frequency of occurrence: 11%, TCC = 99%.

It might come as a surprise that the most frequent cloud regime in what is usually seen as one of the most convective regions of the world is a shallow convective regime, while deep convection is only present in a dominant way in about 30% of all cloud scenes. This may be indicative of two facts. First, the background state of the tropical atmosphere is one of subsiding motion disturbed by intermittent convection. Second, deep and optically thick convective systems are relatively rare compared to the cirrus outflow they may produce and when present rarely cover large areas in the 280 x 280 km grid boxes that form the basis of this study.

Typical Cloud Regimes at the ARM TWP Sites

Having identified typical cloud regimes in the TWP region, we will now investigate how representative the cloud regimes observed at the ARM facilities located in that region are. Two questions are crucial in that respect: (1) Are all the cloud regimes found in the TWP observable at the ARM sites? (2) Which site should be chosen to observe a particular regime maximizing its frequency of occurrence?

To answer these questions the following technique is applied separately for each of the TWP facilities (Manus and Nauru). First, the ISCCP histograms for 1999 are retrieved for the ISCCP grid boxes containing the site. Given the three-hourly nature of the data and its existence only during daytime, around 1500 cloud situations are available at each site from this dataset. Second, the Euclidian distance of each histogram to each of the five cluster centroids identified for the TWP is calculated. The histogram is then placed into the regime for which this distance is smallest. Having assigned each histogram to one of the five regimes, the average histogram within each regime and the frequency of occurrence of the regime at the ARM sites is calculated. The results for both ARM sites in comparison to the TWP results are displayed in Figure 5. Note that the order of the panels reflects the frequency of occurrence of the regimes at Manus, not that of the entire TWP dataset.

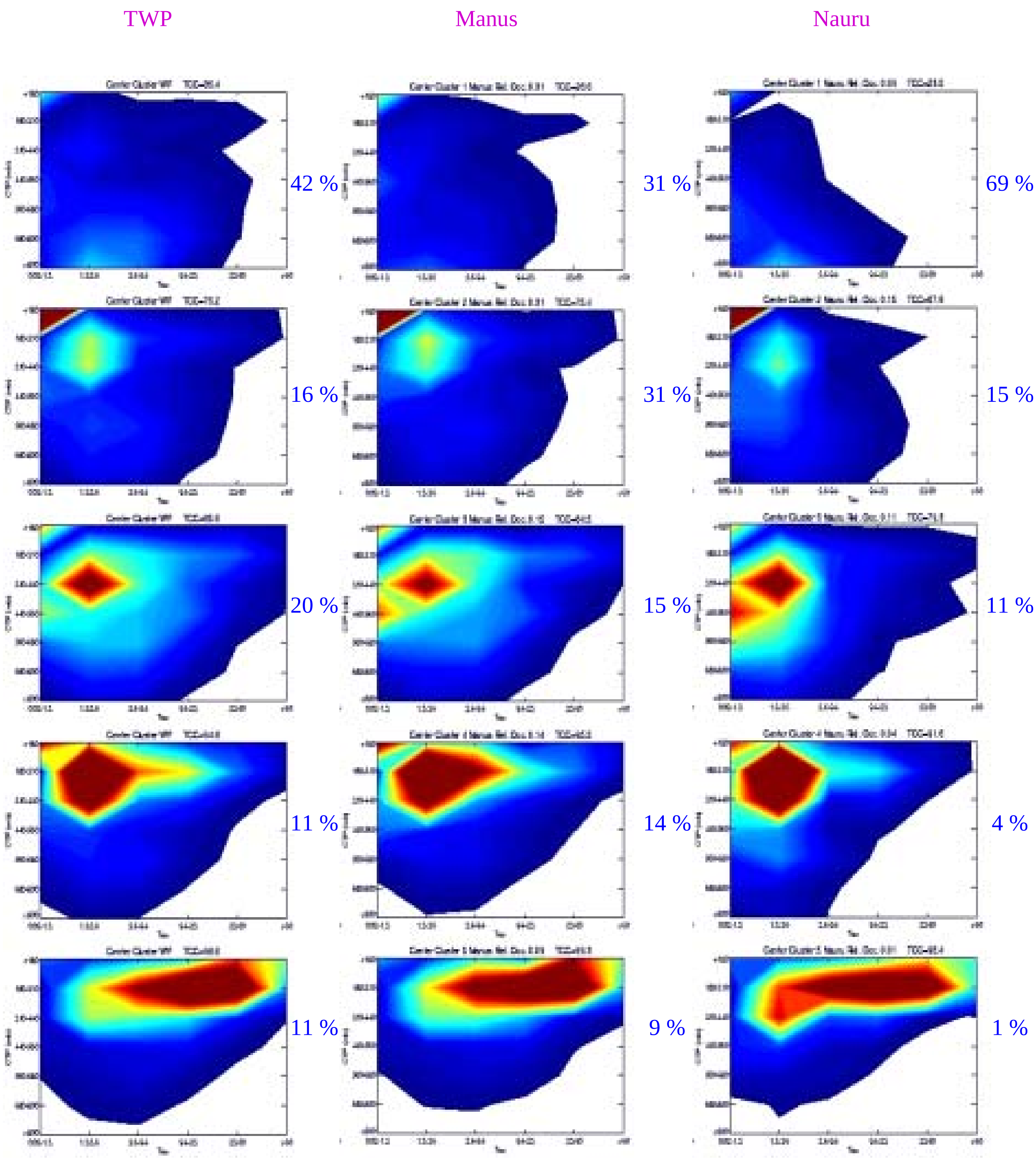

Figure 5. CTP-τ histograms of the centroids of a five-cluster analysis for the TWP (left) and the projected centroids at Manus (middle) and Nauru (right). The numbers to the right of each panel indicate the relative frequency of occurrence of each regime in the given area.

The shallow cloud regime is the dominant regime at both sites, just as in the entire TWP region. However, it occurs on significantly fewer than average occasions at Manus (31% instead of 42%) where it shares the top frequency of occurrence with the transparent cirrus regime. At Nauru, the shallow cloud regime is by far the most frequent in 1999 (69%) and the shape of the mean histogram suggests more strongly suppressed conditions at Nauru than on average in the TWP, indicated by the absence of high cloud tops and a below average TCC of 24%. This is explained by the location of Nauru in the relatively cold sea surface temperature (SST) region at the eastern edge of the TWP warm pool and again confirms in an impressive manner the usefulness of the clustering method in delivering physically sensible results. The next most frequent regime (actually equally frequent at Manus) is that dominated by transparent high-level cirrus. It occurs 31% of the time at Manus, almost twice as frequently as in the TWP, and 15% of the time at Nauru. This is possibly indicative for the closer proximity of the Manus site to convective activity and makes Manus an excellent facility for studying such clouds.

The mid-level top convective cloud regime occurs slightly less frequently than average at both sites. It is however worthwhile noting that this regime is the most frequent of the regimes containing deep convection both at the ARM sites and in the entire TWP. The other two deep convective regimes, one dominated by cirrus the other by optically thicker clouds, occur with about average frequency at Manus, and are extremely rare at Nauru. This does not come as a surprise given the location of the two sites with respect to the SST distribution in the TWP. In this context, it is worthwhile stressing that the results here are only representative for an individual year (1999) and one would expect the picture presented here to change in others years due to changing conditions (e.g., El Niño) conditions. Nevertheless, since 1999 is probably close to a “normal” year with respect to El Niño-Southern Oscillation, we can still draw some conclusions from the results here.

Probably the most important conclusion to be drawn is that between them the tropical ARM sites cover all cloud regimes typically found in the TWP. Nauru appears to be a good site for the study of shallow clouds, although known island effects may make it difficult to use the data alone for that purpose. A second regime suitable for study at this facility is that of mostly thin or transparent cirrus, although maybe surprisingly, Manus provides a more frequent occurrence of this regime. Cloud regimes involving significant amounts of deep convection are best studied at Manus.

Conclusions and Future Work

A cluster algorithm has been applied to ISCCP histograms of cloud-top pressure and cloud optical thickness over the TWP with the aim to identify typical cloud regimes in that region. It has been shown that this algorithm is capable of robustly identifying physically interpretable cloud regimes. Five such regimes have been identified for the TWP region used. The identified regimes have then been used to assess the representativeness of the ARM TWP site facilities at Manus and Nauru for cloud regimes occurring in the broader TWP region. We can conclude that all cloud regimes identified in the TWP do occur over the ARM sites, albeit with very different frequencies of occurrence mostly related to the location of the sites with respect to the SST distribution in the region. For the year 1999 Nauru is dominated by a shallow cloud regime and a transparent cirrus regime with very few occurrences of regimes directly involving deep convection. While the shallow and transparent cirrus regime is also the most frequent at Manus, a significant number of cases involving deep convection occur at that site.

The success of the simple cluster analysis technique in identifying structures in the ISCCP histograms is encouraging us to think about other potential applications of the technique as well as the information obtained in this study for the ARM sites. An obvious extension of the work presented here is the inclusion of other geographical areas in the analysis with them aim to study other cloud regimes and to establish a global picture of their distribution and occurrence. At the ARM sites themselves, the work will be extended into studying the radiative and cloud signatures of the different regimes as revealed by the extensive array of ARM instruments. Finally, the application of regime classifications has proven useful for model evaluation in the past and this technique provides a natural path to an extension of these studies to tropical latitudes.

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