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TEMPORAL SCALES OF THE AREAL COVERAGE AND PRECIPITATION OF MONSOONAL CONVECTIVE CLOUD SYSTEMS OVER THE TROPICAL INDIAN OCEAN

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1. INTRODUCTION

Cloud processes continue to be a significant source of uncertainty in the modeling of the general circulation of the atmosphere. The physics associated with the production of clouds and precipitation critically impacts the radiative forcing of the climate system and the scavenging of trace gases and aerosols, among other effects. Gaining confidence in model predictions requires careful validation against observational cloud climatologies. Development of a comprehensive cloud climatology, however, is hindered by the complex temporal and spatial variability of natural cloud systems.

The typical approach to cloud climatology studies is to prepare time and space-averaged fields of cloud coverage and cloud properties. For the purposes of model validation, these observations are then compared with similar fields generated by a model. This approach ignores the fact that clouds are dynamical entities that evolve with time. Thus the cloud coverage observations in traditional cloud climatologies are often integrations over the temporal and spatial variability associated with several cloud systems.

As an alternative to these studies, a Lagrangian approach is adopted in this study whereby individual clouds are identified and tracked in time using geostationary satellite imagery. A database of the areal coverage and lifetimes of an ensemble of clouds spanning a broad range of time and space scales is produced. The boundaries of each cloud are determined such that they encompass both the active regions of precipitating convection within the cloud as well as the extended decks of anvil and cirrus cloud resulting from convection. Preliminary estimates of rain rate throughout the lifecycles of the observed clouds are made from infrared brightness temperatures in order to investigate the temporal scales of precipitation within evolving cloud systems. The statistical description of cloud spatial and temporal properties that results from this analysis is offered as an additional tool for the validation of cloud parameterizations that can be compared to similar statistics determined for an ensemble of clouds predicted in general circulation model simulations.

The analysis presented here reveals that wintertime monsoonal cloudiness over the tropical Indian Ocean is dominated by giant decks of semi-permanent overcast cloudiness that can cover millions of square kilometers and persist for days to weeks. The evolution of the areal coverage and precipitation of such clouds is modulated by such processes as planetary wave dynamics, moist convection and microphysics. Comparing the evolution of observed clouds to that of modeled clouds will help reveal how well current parameterizations approximate cloud physical processes.

2. DATA AND METHODOLOGY

The temporal and spatial scales of clouds over the tropical Indian Ocean are determined using half-hourly METEOSAT-5 images during the period 1 January through 9 February 1999. Image pixels (gridded at 0.25 deg. lat-lon) are roughly classified by cloud type based on infrared window and water vapor channel brightness temperatures (T_{IR} and T_{WV} respectively). The classification scheme, summarized in Table 1, aims to classify only overcast pixels. Pixels that do not meet the criteria in Table 1 are either clear-sky or only

Table 1. METEOSAT-5 pixel classification scheme

classification	brightness temperature (K)
deep convection/anvil	T_{IR} < 240
shallow conv./thick cirrus	240 <= T_{IR} < 280
thin cirrus	T_{IR} >= 280, T_{WV} < 245

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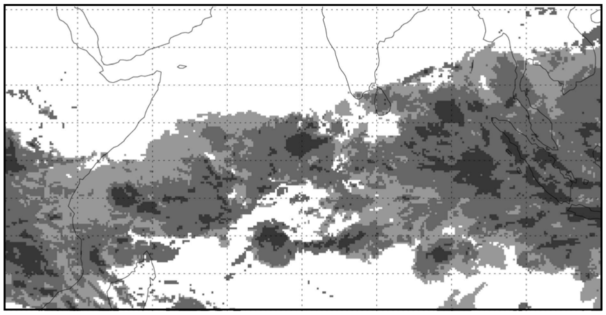

Fig. 1. METEOSAT-5 cloud map from 1100 GMT, 18 Jan. 1999. Black: deep convection/anvil; dark gray: shallow convection/thick cirrus; light gray: thin cirrus.

partially covered by cloud and are disregarded.

Following classification, a cloud-clustering algorithm similar to that described in Mapes and Houze (1993) is applied whereby adjacent overcast pixels are grouped into a single cloud. Overcast pixels must share a side to be included in the same cloud. For the purposes of this study, the term "cloud" refers to a cluster of adjacent overcast pixels.

Once cloud maps have been constructed for a series of consecutive images, an automated cloud-tracking algorithm is applied to them that identifies clouds containing pixels that overlap in consecutive images. A cloud may overlap with several clouds from the preceding image or the subsequent image because of splitting and merging behavior. In such cases, a decision is made about which pair of overlapping clouds are the same cloud by finding the pair whose fractional area of overlap is greatest.

Surface rain rate estimates, averaged over the area of each cloud, are made using a variation of the GOES Precipitation Index technique of Arkin and Meisner (1987). Rain rate (R) is related to f_{240}, the fraction of the area of each cloud with T_{IR}<240K according to the following expression:

$$R(\mathrm{mm/hr}) = G f_{240}$$

where the coefficient, G, is calibrated by passive microwave rain rate measurements from collocated passes of the TRMM satellite. The value of G is 1.28 mm/hr based on a regression between cloud area-averaged rain rate measured by TRMM and f_{240} from METEOSAT-5 for a set of nearly 200 clouds exceeding 5 X 10^5 km^2. The correlation coefficient of the regression is 0.7. The resulting rain estimates are expected to be biased low owing to a small amount of precipitation observed from clouds with temperatures warmer than 240K. The rain estimates are preliminary. More sophisticated IR techniques will be applied in the future.

3. RESULTS

3.1 Cloud Spatial and Temporal Scales

Figure 1 is an example of a METEOSAT-5 image following the classification step in the analysis. The image shown corresponds to a period of widespread convection along the Intertropical Convergence Zone. The dominant feature of the image is a single cloud characterized by a giant overcast deck extending across the ocean basin. Within the overcast deck are numerous areas of active deep convection that provide the cloud material for extended decks of anvil and cirrus cloud that act as bridges connecting the convective regions. During the 40 days of the analysis, a few clouds such as the one shown in Fig. 1 dominate the integrated cloud cover. The dominance comes not only from their large spatial coverage, but also because such giant overcast decks can persist for several days to several weeks.

Fig. 2a shows the number distribution of

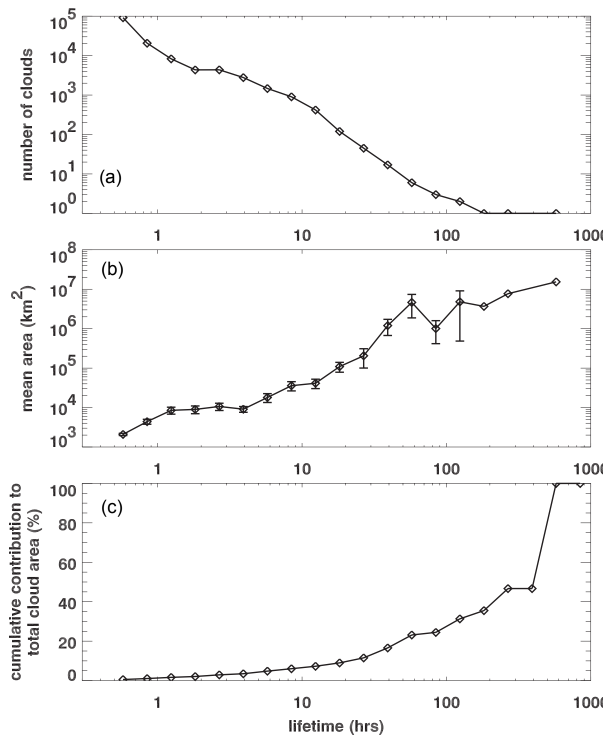

Fig. 2. (a) Number of clouds. (b) Mean area of cloud averaged over cloud lifetime. (c) Cumulative contribution to total overcast cloudiness. All are shown as a function of cloud lifetime. Error bars indicate one standard deviation of the mean.

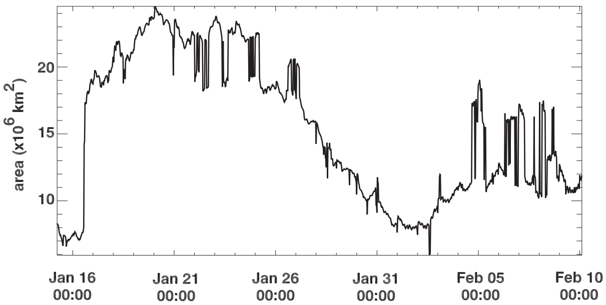

Fig. 3. Temporal evolution of the areal coverage of the longest living cloud observed. An image of this cloud on Jan. 18 appears in Fig. 1.

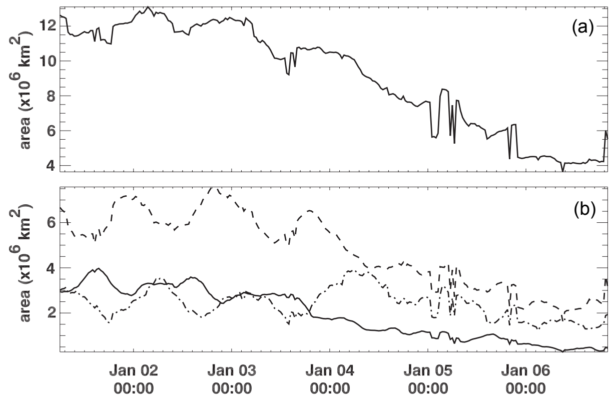

Fig. 4. (a) Temporal evolution of the areal coverage of another cloud. (b) Temporal evolution of the areal coverage of each cloud type within the cloud. Solid line: deep convection/anvil; dashed line: shallow convection/thick cirrus; dash-dot line: thin cirrus.

clouds as a function of cloud lifetime. While over 40 000 individual clouds were tracked for at least 1 hour, only five clouds where found to last for greater than 100 hours. They are also the five largest clouds observed. Averaged over their lifetimes, 4 of the 5 longest living clouds exceed one million km^2 as illustrated in Fig. 2b. The cumulative contribution to the total observed cloud cover is presented in Fig. 2c. Over 75% of the total cloud coverage is attributable to just those clouds that persist for greater than 100 hours.

3.2 Internal Temporal Variability

The temporal evolution of the cloud pictured in Fig. 1 is shown in Fig. 3 over a 26-day period. The size of the cloud demonstrates variability on a number of important time scales. First, there is the growth and decay cycle on a time scale of weeks that is likely a result of planetary wave modulation of deep convection or other large-scale forcing events. The scale of this cloud is so large, however, that it extends across the entire satellite image for a considerable length of time and always borders at least one boundary of the image. Thus the long time-scale evolution of the cloud's area could simply result from movement of the cloud off of the image (such as into the western Pacific Ocean, for example). The second most obvious variation in the evolution of this cloud's area is the fast time-scale flickering, often growing or shrinking by millions of km^2 in a single half-hour time step. Such flickering results from splitting and merging behavior that is especially prevalent when a tenuous bridge of cirrus cloud exists between two large, geographically separated regions of intense convection.

Cloud size varies strongly on the diurnal time scale. Figure 4a is the same as Fig. 3 but for a 7-day period of the lifecycle of another cloud. The area of the cloud oscillates diurnally over 4 days before beginning to dissipate. Figure 4b shows the area of the cloud that is attributable to each cloud type (the sum of each of the three lines in Fig. 4b is the curve shown in Fig. 4a). Deep convection and anvil cloudiness within this cloud tend to peak in the afternoon as illustrated by the area colder than 240K (solid line). The area covered by thin cirrus (dash-dot line) peaks 12-15 hours later and the intermediate cloud class (dashed line) peaks in between. While convection varies on a diurnal time scale, the lag between the peak in convection and the peak in cirrus cloud cover help explain how giant overcast decks persist.

3.3 Precipitation Statistics

The amount of condensate that falls out is a constraint on the amount of condensate available to detrain as anvil and cirrus cloud. Furthermore rain rate and the spatiotemporal scales of precipitation control the amount of soluble trace gas and aerosol that is scavenged. The dependence of precipitation processes upon the temporal scales of clouds is presented in Fig. 5. Rain rate, averaged over the area and lifecycle of the cloud, increases strongly with cloud duration (Fig. 5a). Precipitation is predominantly associated with the same large and long-lived clouds that dominate the total cloud cover. The mean number of precipitating regions (T_{IR} < 240K) also increases strongly with cloud lifetime (Fig. 5b). The longest living clouds typically contain 50 to 100 distinct regions of cold cloud within a single overcast deck at any one time. The probability that a cloud contains a precipitating region at some point during its lifecycle increases with cloud lifetime (solid line, Fig. 5c). Also, the fraction of that lifetime that the cloud precipitates reaches 1 for the longest living clouds (dotted line, Fig. 5c). While clouds at shorter temporal and smaller spatial scales may precipitate for only a fraction of their lifetime (or not at all), large semi-permanent clouds are always precipitating somewhere within their boundaries and typically contain many distinct regions of precipitation. Since such clouds are always precipitating, they never completely decay. Instead they tend to merge with another large cloud prior to fully dissipating.

4. CONCLUSIONS

Parameterization schemes for cloudiness in general circulation models are often based on the assumption that clouds are small relative to the size of the grid cell. Furthermore, cloud condensate, if predicted in a model, is rarely assigned a time constant such as a fall velocity. The observations presented here cast some doubt on these criteria, at least in the context of monsoonal convective clouds. Continuous overcast decks of cloud that are large enough to span numerous grid cells in global GCMs are demonstrated to persist for days to weeks.

The ability for parameterized subgrid-scale processes in the NCAR Community Climate Model to produce clouds with the spatial and temporal scales observed here will be tested in a subsequent study. Since clouds spanning several grid cells dominate the total cloud cover, the model should produce clouds whose boundaries can be detected and tracked in a fashion similar to those in the satellite images. The case studies and statistics presented here will serve as new tools for validating cloud parameterization schemes.

5. REFERENCES

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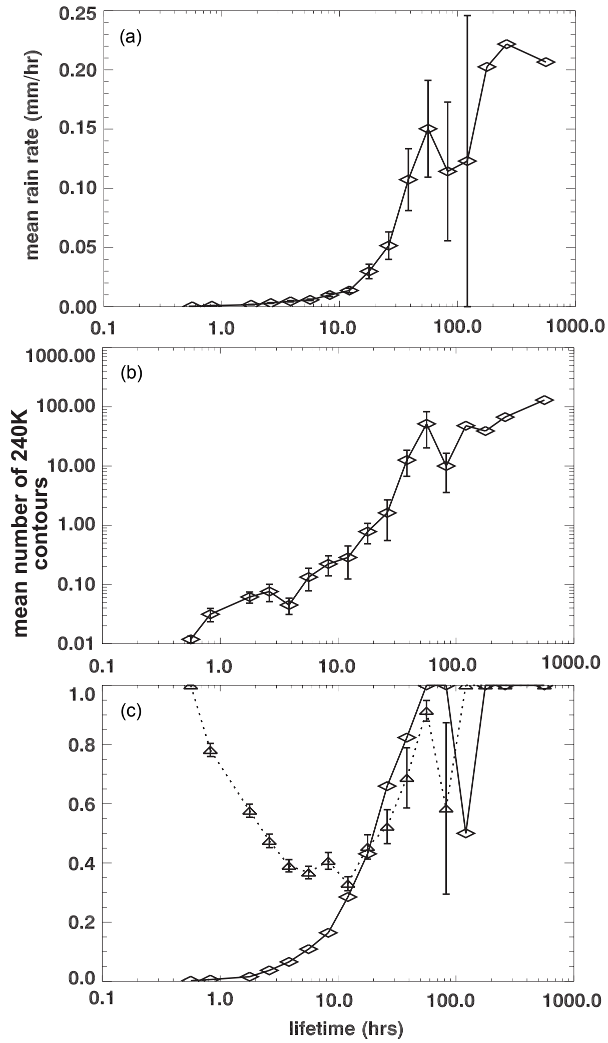

Fig. 5. (a) Surface rain rate averaged over the area and lifetime of the cloud. (b) Number of distinct regions of T_{IR}<240K. (c) Solid line: Fraction of clouds containing a region of T_{IR}<240K. Dotted line: Fraction of cloud's lifetime during which cloud colder than 240K is present (for those clouds containing a 240K contour at some point during their lifetime). Error bars are one standard deviation of the mean.