Mesoscale Convective Complexes in the Western Pacific Region

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ABSTRACT

A climatological study of mesoscale convective complexes (MCCs) during 1983–1985 over the western Pacific region (WPR), using full-disc, enhanced infrared satellite imagery from the Japanese Geostationary Meteorological Satellite is presented.

The results indicate that MCCs are common in the WPR and display many of the same characteristics as those found in the Americas. The systems are nocturnal and tend to form over or in the immediate vicinity of land. Cold-cloud shields in the Americas last for about 10 h while WPR shields last about 11 h. The cold-cloud-shield size distribution is similar to that of the Americas, with most systems exhibiting areas between 2 × 10^5 and 3 × 10^6 km^2. Seasonal distributions of WPR systems are also similar to that in the Americas. Specifically, the frequency of midlatitude systems peaks in late spring and early summer while low-latitude MCCs are distributed uniformly throughout the warm season.

As with western systems, WPR MCCs occur in preferred zones. Climatologically, low-level jets of high-θ_e air and upper-level divergence are present in these zones. Tracks of WPR MCCs show that, like American systems, they typically move to the right (left in the Southern Hemisphere) of the climatological mean 700–500-mb flow. The deviation from the mean flow is in the direction of the source region of highest-θ_e air. A few MCCs that moved over water formed tropical storms. Likewise, a few tropical systems moved over land and formed MCCs.

It is concluded that the strong similarity of the properties and environment of WPR MCCs to that in the Americas indicates that they are essentially the same phenomenon. Their high frequency in the Americas and the WPR makes them potentially important contributors to the global hydrologic cycle.

1. Introduction

During the past decade, mesoscale convective complexes (see Maddox 1980, for definition) have received much attention from researchers in the United States (e.g., Cotton et al. 1983, 1989; Rodgers et al. 1985; Leary and Rappaport 1987). The attention is not unwarranted as Fritsch et al. (1986) and McAnelly and Cotton (1989) found that these long-lived convective weather systems, commonly called MCCs, produce the bulk of the warm-season rainfall over much of the midwestern United States. Moreover, Johnston (1981), Johnson (1986), Menard and Fritsch (1989), and Augustine and Zipser (1986) have shown that MCCs can significantly alter the tropospheric wind flow. In fact, forecast errors of over 30 m s^{-1} at 200 mb have occurred due to MCC effects (Fritsch and Maddox 1981). In addition to the studies of MCCs in the United States, several other investigators have documented MCCs or MCC-like systems in other parts of the world. For example, Houze et al. (1981) and Johnson and Priegnitz (1981) documented mesoscale convective systems (MCSs)\footnote{Zipser (1982) defines an MCS as a cloud and precipitation system (together with its associated circulation systems) that includes a group of cumulonimbus clouds during most of its lifetime.} over the South China Sea during the Winter Monsoon Experiment. These systems exhibited size and life-cycle characteristics that resembled those of MCCs. Similarly, many MCSs in the GARP Atlantic Tropical Experiment (GATE) displayed structures and characteristics similar to MCCs (e.g., see Houze 1977; Leary and Houze 1979; Martin and Schreiner 1981). Hicks (1984) and Wilson and Ryan (1986) have completed studies on MCC-like systems over Australia. Likewise, Browning and Hill (1984) investigated a mesoscale convective system over the British Isles. Most recently, Velasco and Fritsch (1987) completed a study of MCCs over Central and South America.

The present study provides a climatology of MCCs over the western Pacific region (WPR), Northern and Southern hemispheres. By locating regions of frequent MCC occurrence in various parts of the world, and...
documenting the synoptic conditions, it may be possible to find common mechanisms and conditions for their formation, and thereby better understand the dynamics of their development. The reader is cautioned, however, that the limited (3-yr) data sample may be insufficient to provide a stable climatology and that the results should be considered as preliminary.

2. Data, methodology, and MCC definition

Satellite images from the Japanese Geostationary Meteorological Satellite (GMS) were used to perform the present study. Both full-disc enhanced infrared (EIR) and visible images were examined. Fett et al. (1983) gives the characteristics of the GMS VISSR (Visible and Infrared Spin Scan Radiometer) satellite. The GMS is similar to the U.S. Geostationary Operational Environmental Satellite (GOES) and even offers a slightly better IR resolution (5 km as opposed to 7 km for GOES). However, the blackbody temperatures ($T_{bb}$) that can be enhanced only range from +30° to −80°C, whereas GOES ranges from +50° to −110°C. The IR images from GMS are available usually every 3 h starting from 0000 UTC except for a special image taken at 1600 UTC. A total of 11 images, 8 IR and 3 visible, are available per day. The visible images are produced roughly an hour to an hour and a half after the EIR image. Figure 1 shows the enhancement curve for the GMS EIR images used in this study; it was designed to highlight areas of convection. The curve is generally linear until −56°C where the enhancement goes to black. The curve stays black until −70.9°C and then steeply goes to medium gray until −76°C. After that the curve goes to white. Any blackbody temperature < −80°C will appear as white.

Several problems arose in using the GMS imagery. First, the initial enhancement step in the EIR imagery occurred at −56°C. Therefore, one of the criteria Maddox used for his study—i.e., the −33°C blackbody temperature threshold—was not available. On the other hand, since the −56°C blackbody temperature is close to Maddox’s other threshold value, −54°C, it was used in place of the −54°C temperature. This is not considered a serious departure from Maddox’s criteria since it is rare for the −33°C area of a cold-cloud shield not to fulfill Maddox’s criteria when the −54°C area does (see Augustine and Howard 1988). Also, there is precedent for using only the −54°C cold-cloud shield area since Cotton et al. (1989) successfully applied this less restrictive requirement in the development of a composite model of MCCs. Moreover, since −56°C is being used instead of −54°C, the results will actually be slightly conservative. A second problem in using GMS imagery was the time resolution of images (≈ every 3 h). This made the determination of exact times of MCC stages (e.g., first storms, genesis, maximum extent, and dissipation) impossible to pinpoint. Therefore, time periods, e.g., 1200–1600 UTC or 0300–0600 UTC, were used to indicate when a particular stage or event had occurred. For example, if “initiation” was not evident at 1200 UTC but was apparent on the 1600 UTC image it was assumed that initiation occurred at the midpoint time between the two images.

A third problem was look angle. For the full-disc satellite images used in this study, Fig. 2 shows the relationship between cloud-shield area and distance (on the image) from the satellite subpoint. Beyond certain longitudes, the decrease in area becomes intolerable and estimates of cold-cloud-shield area and shape are questionable at best.

A final problem was with the GMS itself. During this time period (1983–85), GMS-2 malfunctioned and GMS-1 was used for a time. Then, GMS-1 failed completely and GMS-2 was reactivated. An entire week of imagery was lost during the GMS-2 malfunction in January 1984. Nine days in February were incomplete. In late May 1984, the GMS-1 images became cutoff south of 10°–15°N. GMS-1 completely failed on 29 June 1984. GMS-2 was reactivated; however, imagery was available only every 6 h as compared to every 3 h previously. This situation continued until September when GMS-3 was activated. With these numerous problems, only about (80%–85%) of the 3-yr period was adequately investigated. Consequently, this study represents a conservative estimate of MCCs in this region.

In view of the aforementioned limitations of the satellite data, the following methodology and definition criteria were adopted. Only systems within the domain bounded by 90°E–170°W and 50°N–50°S were in-

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2 According to McAnelly and Cotton (1989), the two IR thresholds that are shown in the MB-enhanced imagery curve are −33.2° and −54.2°C instead of −32° and −52°C as reported in Maddox’s (1980) MCC definition paper. Therefore, we are following Cotton et al. (1989) by referring to Maddox’s criteria as −33° and −54°C.
that the relationship between the active core area and the $-33^\circ$C area for the American systems is similar for the WPR systems, the resulting value of the ratio ($\approx 2.17$) was then multiplied times the area of the WPR systems. Table 1 summarizes the criteria used for this study.

Finally, it is important to note that even though mesoscale convective systems may fulfill all the satellite-based MCC criteria outlined above, it is entirely possible that the internal structure of individual systems may be very different from case to case and from region to region (e.g., see McAnelly and Cotton 1986). This is especially true when considering the diversity of convective environments around the globe. On the other hand, the fact that the MCC criteria are only fulfilled in a small fraction of the areas of the world that experience deep convection clearly indicates that there must be special environmental conditions present where MCC cold-cloud shields are observed. The criteria outlined in Table 1 were applied uniformly to all systems with the following exception. In some instances, tropical storms/typhoons produced cold-cloud shields that met the MCC criteria. These events were not included in the MCC sample. However, if a convective system qualified as an MCC prior to becoming a tropical storm, it was included in the dataset until which time it reached tropical storm strength.

3. Results

The date, latitude, longitude, lifetime, size, and any observational remarks for 206 convective systems, which matched the criteria specified in section 2, are listed in Miller (1990). Note that unlike in Maddox’s (1980) study of MCCs in the United States, storm data from the countries affected were not available. Therefore, it is not possible to provide an estimate of the severe weather frequency with WPR MCCs.

Considering that 206 systems occurred in less than a 3-yr period, it is obvious that MCCs are a common occurrence in the western Pacific region. The maximum number of systems per year, 89, occurred in 1983; 1985 was second with 75, and 1984 had the least with

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**TABLE 1. Definition of MCCs in the eastern hemisphere.**

| Size: | Cloud shield with continuously low IR temperature $< -56^\circ$C must have an area $> 50,000$ km$^2$. |
| Initiate: | Size definition is first satisfied. |
| Duration: | Size definition must be met for two time periods (one time period $= 2-3$ h), but no less than 5 h total. |
| Maximum extent: | Observed maximum size of the contiguous cold-cloud shield (IR temperature $< -56^\circ$C). |
| Shape: | Eccentricity (minor axis/major axis) $> 0.7$ at time of maximum extent. |
| Terminate: | Size definition no longer satisfied. |
42. The small number in 1984 was mostly due to satellite problems (see section 2) rather than an anomalously low frequency. Some general characteristics of the set of all systems, Northern and Southern hemisphere systems combined, are presented first. These are followed by results that focus on major subregions. It is important to note that wherever mean annual properties of MCCs are presented, they are based on the two years for which data was essentially complete (1983 and 1985).

a. Life cycle and duration

The life cycle of the set of all systems (Fig. 3) is very similar to that documented for systems in the Americas (Maddox 1980; Velasco and Fritsch 1987; Cotton et al. 1989). In particular, the systems are distinctly nocturnal. First, thunderstorms typically developed in the late afternoon (about 1600 LST) with MCC genesis occurring during the evening or early nighttime hours (around 2200 LST). Maximum extent of most systems occurred between 2300 and 0500 LST, dissipation occurred most frequently around 0800-1000 LST. This tendency for the systems to maximize at night was also found by Johnson and Kroie (1982) and Williams and Houze (1987) in their studies of MCSs over the South China Sea.

The frequency distribution of the duration of all systems is shown in Fig. 4. Average duration was approximately 11 h and the modal duration was around 9 h. The distribution and the average are very similar to the distribution and average for MCCs in the Americas (see Velasco and Fritsch 1987). For example, the average duration for all American systems (including low-latitude and midlatitude North and South American systems) is approximately 10 h. Figure 4 also shows the frequency distribution of duration for the Northern and Southern hemispheres individually. Although there were fewer systems in the Southern Hemisphere, the distributions are essentially the same.

b. Cold-cloud-shield size distribution

The size distribution of WPR MCCs along with a comparison to the American systems is shown in Fig. 5. Clearly, the distributions are very similar. The category of cold-cloud-shield area $A$ of greatest frequency is $2 \times 10^5 < A \leq 3 \times 10^5$ km$^2$, and the maximum areas are about $10^6$ km$^2$. Cold-cloud shields this large, rival and even exceed the cloud shields with many synoptic-scale systems.

c. Seasonal characteristics

The monthly distributions of mid- and low-latitude populations of western Pacific region MCCs for 1983

![Fig. 3. Life cycle of western Pacific region MCCs. Frequency curves were smoothed with a three-point running mean.](image)

![Fig. 4. Frequency distributions of duration of western Pacific region MCCs. Distributions were smoothed with a three-point running mean.](image)

![Fig. 5. Frequency distributions of MCC cold-cloud-shield maximum area. Solid line is for 1983-85 western Pacific region; dashed line is the distribution for a 2-yr period in the Americas (see Velasco and Fritsch 1987).](image)
tend to become higher than over the surrounding water bodies.

In addition to the correlation of MCC activity to the sun angle, there also appears to be a connection between MCCs and upper-level jet streams. For example, Velasco and Fritsch (1987) showed that as the midlatitude jet stream migrates latitudinally over North America, the center of MCC activity migrates with it. The MCC activity maintains its same relative location with respect to the jet and the axis of the low-level high-$\theta_e$ air that feeds the convection. In areas where there is little latitudinal migration of the jet, such as the ocean-dominated Southern Hemisphere, there is little movement of the MCC region, for example, over midlatitude South America. Figure 7 shows that in the WPR, Northern Hemisphere midlatitude MCCs also exhibited a tendency to migrate poleward during the summer. Since there were only three MCCs that occurred in the WPR Southern Hemisphere midlatitudes, it was not possible to make a comparison to South American midlatitude systems. Note, however, that low-latitude systems showed little latitudinal movement.

d. Geographic distribution

Although convective systems were observed to occur throughout the western Pacific region, Fig. 8 shows that there are certain zones that are more favorable for MCC genesis than others. In particular, there appear to be four distinct population centers:

(i) northern Australia
(ii) New Guinea
(iii) northeast India/Bangladesh
(iv) mainland China/South China Sea

This tendency for MCCs to be concentrated in only a few areas, even though many areas have frequent and
extensive deep convection, was noted by Velasco and Fritsch (1987). They pointed out that the favored areas have several things in common. Specifically, they noted that systems tended to form 1) over land, 2) in the lee of mountain ranges, 3) in areas frequented by low-level jets of high-$\theta_e$ air, and 4) where convective available potential energy (CAPE) was large relative to surrounding areas. They also noted that systems that formed over water sometimes developed into tropical storms. In general, based upon the locations of systems in this study, some of the same observations can be made. For example, using the direction of the mean upper-level (200-mb) flow to define “upstream” and “downstream” (relative to a given mountain range), the New Guinea and mainland China populations occur in the lee of major ranges. The Australian and northeast India/Bangladesh populations are difficult to categorize since they occur beneath large anticyclone centers (Sadler and Wann 1984), and winds are highly variable throughout their respective warm seasons. Most of the population centers occur downstream of a long fetch of low-level flow over very warm water. For example, the gradient-level flow feeding the China and India/Bangladesh populations is predominantly from the south and southwest and passes over either the South China Sea (China populations) or the Bay of Bengal (India/Bangladesh populations), where water temperatures are typically in excess of 28°C in the May–July period. The gradient-level flow feeding the Australian and New Guinea populations is predominantly from the west and northwest and passes over the Timor and Araufura seas where water temperatures are also in excess of 28°C during the November–January period. Mean monthly cross sections through the most active MCC regions (Ramage and Raman 1972) indicate that low-level jets are typically present in each region during the warm seasons. Moreover, there is even a low-level easterly jet over the open ocean east of the Philippines (10°–30°N, 140°E) during the fall and early winter when most of the MCCs (and many of the tropical storms) develop in that region (Fig. 8). It is recognized that climatological conditions are not necessarily a good indicator of conditions during individual MCC events. However, based upon the studies of many MCC events in the Americas (e.g., Maddox

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3 The gradient level is defined as the lowest level at which predominantly friction-free flow occurs. This is typically near 1 km MSL over most of the tropics.

4 The physiographic relationships between the MCC population centers and the mountains, ocean currents, and climatological low-level flow are shown in Miller (1990). Sea surface temperatures are available from Sadler et al. (1987a,b); ocean currents from Bartholomew and Son (1977); and low-level winds from Atkinson and Sadler (1970).
1983; Merritt 1985) and upon a sampling of WPR cases, the climatological conditions in the regions of frequent MCC occurrence give a good indication of the general large-scale environment favorable for MCC development.

Unlike the MCC population in the Americas, WPR systems did not exhibit a strong bias for developing over land. About half of the total population formed over water. However, this result may be somewhat misleading. Consider that in the Americas there are few land areas other than the major continents, whereas in the western Pacific basin there are many large islands. It is evident from Fig. 8 that many systems occurred very near coastlines and their genesis may have been influenced by the presence of the nearby land area. In fact, if all systems within 250 km of the land areas shown in Fig. 8 are included in a category of events termed “land-related systems,” then over 80% of the MCCs fall within this category.

From Fig. 8, it is also evident that very few MCCs formed in Burma and Thailand even though there is strong speed convergence and pronounced low-level onshore flow from the Bay of Bengal (Atkinson and Sadler 1970). This is very similar to the situation in middle America where speed convergence and onshore flow from the Gulf of Mexico result in few MCCs in that region as well (Velasco and Fritsch 1987). An explanation for the dearth of systems in these two regions remains elusive.

Of the 102 systems that formed over water, 5 developed into tropical storms (Fig. 8). It is possible that MCCs were responsible for additional tropical cyclogenesis since it has been documented that the warm-core vortices that develop with MCCs sometimes persist for several days and redevelop into new mesoscale convective systems (e.g., Menard and Fritsch 1989; Murphy and Fritsch 1989). In this context it is important to point out that the coastal waters around Australia are breeding grounds for tropical cyclones during the warm season months. Several come on shore and their remnants can continue for days. These remain sometimes spawned convective systems that matched the MCC criteria.

e. Tracks

Studies of the movement of MCCs in the Americas indicate that most systems tend to move to the right (left in the Southern Hemisphere) of the mean wind in the 700–500-mb layer (e.g., see Merritt and Fritsch 1984; Shi and Scofield 1987; Velasco and Fritsch 1987). For the most part, the same relationship appears to hold true in the present study. For example, Fig. 9 shows the tracks for three of the four population centers. (The India/Bangladesh population is not shown because of the low satellite-look angle for that region; see the discussion in section 2.) In general, MCCs in the China region move toward the east or southeast.

For the late spring/early summer period when MCC activity is peaking in southern China, the prevailing flow in the 700–500-mb layer is southwest to southwesterly (Ramage and Raman 1972). In the northern Australia region, MCCs tend to move toward the west and northwest, while in the New Guinea area they move toward the west and southwest. The prevailing 700–500-mb flow in northern Australia in summer is from the southeast (Ramage and Raman 1972). Hence, as expected, systems there tend to propagate to the left of the prevailing midlevel flow. In the New Guinea region, however, the prevailing midlevel flow is from the west-northwest so that most systems are propagating to the right of the prevailing midlevel flow. This is anomalous to all the other Southern Hemisphere MCC populations. It is important to note, however, that like the systems in the Americas, the departure of the WPR systems from the direction of the prevailing midlevel flow tends to be toward the source of the low-level high-θ_e air (see Merritt and Fritsch 1984). For example, the New Guinea systems deviate toward the prevailing low-level westerly flow that crosses the warm Arafura Sea; China systems deviate southward toward the prevailing southerly flow passing over the warm South China Sea. Thus, it remains to determine whether systems tend to propagate to the right (left in the Southern Hemisphere) of the midlevel flow for dynamic reasons (e.g., see Rotunno and Klemp 1982) or whether the rightward deviation occurs simply because the low-level high-θ_e air feeding the convection is almost always to the right (left) of the prevailing midlevel flow.

f. Comparison of WPR and American populations and subpopulations

Table 2 presents some of the mean characteristics of MCC populations and subpopulations for the Americas and the WPR. As noted in previous sections, it is evident that the various populations exhibit strong similarities. In particular, all the populations are nocturnal, grow to about the same size, and persist for roughly the same duration. Analyses of the characteristics of WPR subpopulations present a similar picture. Furthermore, the distributions of MCC duration and area for the four subpopulations evident in Fig. 8 were very much the same (Figs. 10 and 11). Still further, all the subpopulations were predominantly nocturnal (Miller 1990). The only significant differences that were found in the subpopulations were in the monthly distributions. These differences, however, are expected since the large-scale dynamic and thermodynamic regimes that favor organized deep convection in the Northern and Southern hemispheres vary greatly with the seasonal solar cycle.

4. Satellite-observed examples

Seven MCCs have been selected for presentation. These occurred in the following locations:
Fig. 9. Tracks of MCCs. Dots indicate pregensis (first storms) stage; solid line indicates MCC path between genesis and dissipation; dashes indicate dissipating–remnants stage. Circled numbers correspond to the number of the system listed in Miller (1990) and also indicate the point of maximum cold-cloud shield extent during the lifetime of the system. Hurricane symbols indicate when an MCC transformed into a tropical storm; plus (+) signs indicate the presence of a preexisting low-level cyclonic circulation, possibly a residual circulation from a tropical cyclone or depression. (a) 1983–1985 northern systems; (b) 1983–1985 southern systems. Shading in (a) indicates average location of ≥28°C sea surface temperature in June. Shading in (b) as in (a) except for January.

(i) mainland China  
(ii) South China Sea  
(iii) Bangladesh  
(iv) Australia  
(v) Australia (redevelopment of tropical disturbance)
Table 2. Summary of mean characteristics of MCCs in the western Pacific region and the Americas. Numbers in parentheses include systems west of 90°E.

<table>
<thead>
<tr>
<th>Time (LST)</th>
<th>Average systems per season</th>
<th>First storms</th>
<th>Genesis</th>
<th>Maximum observed extent</th>
<th>Dissipation</th>
<th>Duration (h)</th>
<th>Area, (-33^\circ)C ((\times 10^5 \text{ km}^2))</th>
<th>Area, (-56^\circ)C ((\times 10^5 \text{ km}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia and surrounding waters</td>
<td>20</td>
<td>1400</td>
<td>0000</td>
<td>0600</td>
<td>1000</td>
<td>10.0</td>
<td>338</td>
<td>156</td>
</tr>
<tr>
<td>New Guinea</td>
<td>7</td>
<td>1630</td>
<td>2300</td>
<td>0430</td>
<td>0930</td>
<td>10.5</td>
<td>255</td>
<td>118</td>
</tr>
<tr>
<td>China and South China Sea</td>
<td>21</td>
<td>1400</td>
<td>2230</td>
<td>0600</td>
<td>0930</td>
<td>11.0</td>
<td>323</td>
<td>149</td>
</tr>
<tr>
<td>Bangladesh/northeast India/Bay of Bengal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>10 (30)</td>
<td>1400</td>
<td>0000</td>
<td>0800</td>
<td>1030</td>
<td>10.5</td>
<td>399</td>
<td>183</td>
</tr>
<tr>
<td>Total: western Pacific region (1983 and 1985)</td>
<td>24 (27)</td>
<td>1400</td>
<td>2300</td>
<td>0730</td>
<td>1030</td>
<td>11.5</td>
<td>343</td>
<td>158</td>
</tr>
<tr>
<td>United States (1978, 1981, 1982)</td>
<td>34</td>
<td>1500</td>
<td>2100</td>
<td>0130</td>
<td>0630</td>
<td>9.5</td>
<td>299</td>
<td></td>
</tr>
<tr>
<td>Midlatitude, South America</td>
<td>39</td>
<td>1900</td>
<td>2130</td>
<td>0300</td>
<td>0900</td>
<td>11.5</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>Low-latitude</td>
<td>57</td>
<td>2300</td>
<td>0200</td>
<td>0530</td>
<td>1030</td>
<td>8.5</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Over land</td>
<td>28</td>
<td>2230</td>
<td>0100</td>
<td>0530</td>
<td>0930</td>
<td>8.5</td>
<td>323</td>
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<tr>
<td>Over Sea</td>
<td>29</td>
<td>0000</td>
<td>0230</td>
<td>0630</td>
<td>1130</td>
<td>9.0</td>
<td>316</td>
<td></td>
</tr>
<tr>
<td>Total: United States, low-latitude, and midlatitude South America</td>
<td>130</td>
<td>2000</td>
<td>2300</td>
<td>0400</td>
<td>0900</td>
<td>10.0</td>
<td>364</td>
<td></td>
</tr>
</tbody>
</table>

(vi) New Guinea
(vii) The first three MCCs are depicted in Fig. 12. Examination of the upper-air data with this multisystem event indicates that the MCCs were associated with a puzzling series of very short (\(\lambda \approx 10^3 \text{ km}\)) waves embedded in a locally warm zone of mid- to upper-level westerlies. The structure and dynamics of these waves, and their relationship to the MCCs, is an interesting problem that requires much further study.

The fourth example is of an MCC over northeastern Australia (Fig. 13). Included in the satellite image is Tropical Storm Perry (east of the Philippines). Note the strong similarity in the size and shape of the cold-cloud shields of Perry and the MCC. Except for the cloud bands indicating rotation in Perry, the two systems are nearly identical. This strong similarity between cold-cloud shields of MCCs and developing tropical depressions and tropical storms has been observed in several other areas of the world (Velasco and Fritsch 1987). It is also evident in Fig. 13 that there is a remarkable symmetry (with respect to the equator) of the cloud pattern over the western Pacific region. Landier (1990) documents several examples of the formation of tropical cyclone twins that develop symmetrically (with respect to the equator) in response to westerly wind bursts along the equator. The present case strongly resembles the events documented by

![Fig. 10. Frequency distribution of duration for subpopulations of western Pacific region MCCs.](image1)

![Fig. 11. Frequency distribution of cold-cloud-shield maximum area for subpopulations of western Pacific region MCCs.](image2)
Lander, except that the Southern Hemisphere cyclonic circulation counterpart to Tropical Storm Perry was forced to develop over land and, therefore, was manifested as an MCC instead of a tropical storm.

Case example 5 presents further evidence of the direct relationship between MCCs and tropical disturbances. In particular, Fig. 14a shows the enhanced-infrared–observed cloud distribution associated with a very weak tropical disturbance that drifted southward into central Australia from the Gulf of Carpentaria. The disturbance is centered around 19°S, 138°E. Four hours later (Fig. 14b), a small circular, cold-cloud shield is evident at approximately the same location. This system continues to develop and grows into a mature MCC by 2100 UTC 14 December (Fig. 14c). As the high-level cold-cloud shield dissipates, a mesoscale cyclonic circulation is evident in the residual low- and midlevel clouds (Fig. 14d). The following night, a second and even larger MCC develops in the center of the weak tropical disturbance (Fig. 14e). As the high-level cold-cloud shield dissipates once again, the cyclonic circulation, now larger and better defined, is clearly evident in the middle and low clouds (Fig. 14f). This apparent amplification of a warm-core cyclonic disturbance over land is similar to a United States case documented by Murphy and Fritsch (1989).

The sixth case example shows a typical MCC over New Guinea (Fig. 15a). Note that the cold-cloud shield of the New Guinea system is similar in size to that of Tropical Storm Ellis (9°N, 150°E). The large system east of the Philippines is Typhoon Dot. The remaining two systems over the tropical Pacific are typical tropical cloud clusters. For this case, several additional interesting observations can be made. In particular, note the remarkably similar wavelengths (≈1600 km) of the four systems at 10°N. Note also that the size of an individual MCC is much smaller than that of a tropical cloud cluster. And finally, note that 14 h later, when the diurnal radiation cycle has reversed, the sharply defined and well-organized cold-cloud shields of all the various types of weather systems (including the extratropical system near 45°N) have virtually disappeared (Fig. 15b). This suggests that the nocturnal organization and intensification of MCCs is not peculiar to MCCs alone. Rather, nocturnal organization and intensification evidently occur in many different types of weather systems around the world and apparently are strongly linked to a global diurnal cycle (see Gray and Jacobson 1977; Webster and Stephens 1980; and Caracena and Fritsch 1983, for further discussion of this point).

The final example is an open ocean event that occurred near 9°N, 145°E on 21 November 1983 (Fig. 16). On this day, aircraft reconnaissance could not find a closed circulation, despite the large amount of deep convection. The following day, however, a closed surface circulation was observed and the system subsequently went on to become Tropical Storm Ruth. The intense system near the Philippines in Fig. 16 is Typhoon Orchid.

5. Summary and concluding remarks

Using the Japanese GMS, 206 MCCs were found over the western Pacific region during 1983–1985. The characteristics of these systems were very similar to the characteristics of MCCs over the Americas. This was especially true for the systems’ life cycle, duration, seasonal distribution, and size distribution of the cold-cloud-shield areas. Most MCCs formed in the late evening, reached maximum extent during the night and dissipated in the morning. Late spring to early summer was the period of greatest frequency for midlatitude MCCs, while low-latitude systems were distributed more uniformly throughout the warm season. The most frequent size of the cold-cloud-shield area was between...
$2 \times 10^5$ and $3 \times 10^5$ km$^2$, which is similar to the average size of North American systems. Propagation characteristics of western Pacific region MCCs were also similar to those in the Americas. Specifically, most systems tended to propagate to the right (left in the Southern Hemisphere) of the climatological mean flow in the 700–500-mb layer. As with systems in the Americas, the departure of the MCC movement from the mean flow was toward the source of the low-level high-$\theta_e$ air.

In the western Pacific region as well as in the Americas, there appears to be favored regions of MCC development. However, not nearly as great a fraction of the systems in the western Pacific region are concen-
FIG. 15. Enhanced infrared satellite images for (a) 1600 UTC 18 October and (b) 0600 UTC 19 October, 1985.
trated in the favored areas as in the Americas. Clusters of systems tended to form downwind of major mountain ranges (the exception was Australia) and in areas where low-level jets of high-$\theta_v$ air typically occur. Like the Americas, the great majority (>80%) of systems formed either over land or in the near vicinity (within 250 km) of land. A peculiar aspect of the geographic distribution of MCCs is that there are places where the environment is often favorable for deep convection but MCC development is at a minimum if not unfavorable. These include the Amazon Basin, southeastern United States, Burma, and Thailand. It is possible that these differences in location and frequency, especially the land–sea differences, may be important in understanding a variety of climate-related processes (e.g., the relative frequencies and magnitudes of venting of “dirty” boundary-layer air directly into the stratosphere).

Maddox (1983) showed that midlatitude MCCs typically occur in association with a weak disturbance propagating within an upper-level current of locally fast flow, that is, a jet stream. Velasco and Fritsch (1987) found that each of the four MCC population centers in the Americas is located in the vicinity of an upper-level jet. Specifically, for each hemisphere, there is one population center near the midlatitude westerlies and another near the tropical easterlies. As the westerly jet in North America migrates northward, so does the associated area of midlatitude MCCs. In South America, the westerly jet remains virtually stationary during the warm season and so does the center of activity of midlatitude MCCs. In the western Pacific region, there is also a tendency for Northern Hemisphere midlatitude MCCs to shift poleward from spring to summer as the climatological westerly jet migrates northward. Since there were only three midlatitude MCCs in the western Pacific region Southern Hemisphere, it was not possible to establish any relationship between Southern Hemisphere westerlies and MCC activity.

Nevertheless, the results from the Americas and from the Northern Hemisphere midlatitude systems examined in the present study suggest that midlatitude MCCs are more likely to occur in an environment with a sustained supply of high-$\theta_v$ air at low levels and a locally strong current containing relatively weak mesoscale disturbances at upper levels.

Mesoscale convective complexes also appear to be related to tropical storms. This relationship works both ways: MCC vortices sometimes form into tropical storms and sometimes the remains of tropical storms or depressions form into MCCs. Five of the overwater systems in the western Pacific region formed into tropical storms. At the same time, at least three previous tropical systems later met MCC criteria when their remains came on shore (Additionally, such events were evident over the Indian subcontinent. Unfortunately, given the very low look angle of the GMS, the systems over the India subcontinent could not be investigated adequately). The relationship between MCCs and tropical storms has been discussed in several other studies (Zhang and Fritsch 1988; Menard and Fritsch 1989; Murphy and Fritsch 1989) and lends credence to the dynamic definition of an MCC offered by Cotton et al. (1989); i.e., an MCC is a mesoscale convective system that is nearly geostrophically balanced and whose horizontal scale is comparable to or greater than the Rossby radius.

The results of this study indicate that MCCs are not unique to the Americas. Rather, the picture that emerges is that they are an ubiquitous phenomenon that affects a great many areas around the world. Since they transport vast amounts of mass, moisture, and momentum, it would seem that they must play an important role in the global hydrologic cycle. Additional studies to fully document their global distribution should be completed. For example, studies of the MCC populations over the Indian subcontinent using Insat (India geostationary satellite) and over the African continent using Meteosat (from the European community) could be added to the results obtained in this study and to the American climatologies to construct a global climatology. By comparing MCC populations from all over the world we may further understand their relationship to large-scale processes and to the global hydrologic cycle.

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