Regional variation of morphology of organized convection in the tropics and subtropics

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[1] Properties of organized convection with large horizontal area (> 1000 km²) and with different horizontal structures in the tropics and subtropics are investigated by using 14 years of Tropical Rainfall Measuring Mission observations. First, the convective features (CFs) are defined as contiguous areas of convective precipitation detected by the Tropical Rainfall Measuring Mission precipitation radar. Using the minor and major axes of fitted ellipses, the morphology of the CFs are described as closer to a circular or a line shape. Regional variations and the properties of organized convection are examined with CFs with area > 1000 km² after categorizing them by their shapes. Organized convection tends to have larger extent and a higher fraction of near-circular shapes over land than over ocean. Shallow organized convection with maximum radar echo top height below 4.5 km is found mainly over ocean and some coastal regions. Of all tropical oceans, most shallow organized convection is found over the east Pacific. The fraction of line shaped organized convection is higher over the ocean than over land, and is higher in the subtropics than in the tropics. More convective lines are found in winter than in summer over oceans, but more in summer over land. Organized convective lines are slightly less convectively intense indicated by lower 30 dBZ echo top heights and warmer 37 GHz brightness temperatures than those with near-circular shapes. Orientations of organized convective lines are often aligned with fronts, dry lines, warm ocean currents, coastlines, and mountain slopes. Over the subtropics, organized convective lines are tilted more east-west over land, and more north-south over oceans. The largest and the most intense convective lines are found over central Africa, Argentina, and southeast U.S. over land, and over several warm currents in subtropical oceans.


1. Introduction

[2] It is well known that mesoscale convective systems (MCSs) account for a large proportion of precipitation in both the tropics and the subtropics [Nesbitt et al., 2000; Houze, 2004]. They also generate large areas of clouds that play an important role in the radiation budget [Liou, 1986]. Although in general MCSs consist of regions with convective and stratiform precipitation and nonprecipitating regions with anvil cloud, they have a large variety of precipitation and cloud structures [e.g., McAnelly and Cotton, 1989; Johnson et al., 2005]. Different organizations of MCSs can occur under different environments [e.g., Hodges and Thornicroft, 1997; Lemone et al., 1998; Carbone et al., 2002; Johnson et al., 2004]. As a result, they may appear with different morphologies, sometimes as a near-circular shaped, long lasting mesoscale convective complex [e.g., Maddox, 1980], or as a convective line, often with a typical leading line of convection and a trailing area with stratiform precipitation [e.g., Houze, 1977; Zipser, 1977].

[3] During the formation of an MCS, convection becomes organized and sustained. This organized convection is dominant in the life cycle of an MCS. Focusing on the mechanism of leading line/trailing stratiform type of MCSs, many studies have shown that organization of the convection is related to vertical wind shear and convective available potential energy [e.g., Moncrieff and Green, 1972; Houze, 1977; Rotunno et al., 1988; LeMone et al., 1998; Johnson et al., 2004]. If there is significant vertical wind shear at low (middle) levels, convection is usually aligned normal (parallel) to the wind shear direction [LeMone et al., 1998; Johnson et al., 2004; Cetrone and Houze, 2006], and this difference may affect how much stratiform precipitation is generated. Because the latent heating profiles for the convective and stratiform regions are different, this directly influences the vertical distribution of latent heat release [Houze, 1977; Zipser, 1977].
The organized convection also plays a major role in the momentum transport. The buoyancy field from organized convection in MCSs increases the pressure gradient and in turn increases the horizontal momentum near the convective region. The momentum can be redistributed by vertical eddy flux from updrafts and downdrafts [LeMone, 1983; Yang and Houze, 1996; Parker and Johnson, 2000]. This is a major issue for parameterization in large-scale models [e.g., Wu and Moncrieff, 1996] and is particularly troublesome because the momentum flux may be either down-gradient or up-gradient, depending upon relationship between line orientation and the vertical shear vector [Lemone, 1983]. Furthermore, different convective organization may also vary surface flux by manipulating the spread rate of the anvil and cold-pool and the properties of air reaching the surface in the downdraft [Saxen and Rutledge, 1998]. Therefore, organized convection and its associated stratiform precipitation tightly interact with the larger-scale environment over the tropics and subtropics.

Many studies of organized convection are based upon observations from field campaigns, such as the GARP Atlantic Tropical Experiment (GATE) [Cheng and Houze, 1979; Söke and Zipser, 1986], Equatorial Mesoscale Experiment [Alexander and Young, 1992], The Tropical Ocean Global Atmosphere Coupled Atmosphere-Ocean Response Experiment (TOGA-COARE) [LeMone et al., 1998], and the South China Sea Monsoon Experiment [Lau et al., 2000] whereas some are based on model simulations [Moncrieff and Green, 1972; Rotunno et al., 1988]. In recent years, an increasing quantity of satellite observations provides opportunities to describe MCSs from a global perspective [Laiing and Fritsch, 1997; Nesbitt et al., 2000; Schumacher et al., 2004]. The structures of MCSs are found to have important differences with stronger convection over land, but a relatively larger stratiform region over ocean [e.g., Schumacher and Houze, 2003a, 2003b; Robinson et al., 2011]. However, we are unaware of any literature focusing on the organization of convection in these MCSs, or their morphology, from a global perspective.

This study presents the global distribution of organized convection over the tropics and subtropics using 14 years observations from the Tropical Rainfall Measuring Mission (TRMM). TRMM satellite measurements began in December 1997 and continue as of this writing. The instrument suite is described by Kummerow et al. [1998]. These measurements not only are invaluable for global precipitation estimates [Adler et al., 2000; Schumacher and Houze, 2003a, 2003b; Hirose and Nakamura, 2004; Liu, 2011], but also have provided a unique opportunity to study the properties of precipitating cloud systems [Nesbitt et al., 2000; Peterson and Rutledge, 2001; Toracinta et al., 2002; Schumacher and Houze, 2003a, 2003b; Liu and Zipser, 2009; Rotunno and Houze, 2011]. Furthermore, the high vertical resolution of the TRMM Precipitation Radar (PR) permits quantification of the vertical and horizontal structure of MCSs in the tropics and subtropics. With large samples of 14 years of TRMM observations during 1998–2011, the morphology of organized convection over different regions can be described with a statistical approach. Past observational and numerical simulation studies suggest that the morphology of the convection could be tightly related to the large-scale environments, especially the convective lines [Houze and Cheng, 1977; Rotunno et al., 1988; LeMone et al., 1998]. However, MCSs with large area of stratiform region, as the “history” of past convection, could have very complicated horizontal structures. Therefore, it is important to examine the morphology of convective regions in MCSs, which could be more related to the large-scale environments. By combining the TRMM observations and the reanalysis data, it is also possible to improve our understanding of the interaction between large-scale environments and mesoscale convective organization. As the first step toward understanding the organized convection, the focus of this study is to present the regional variations of organized convection and its properties. The specific questions to be addressed include:

(1) What are the differences in the properties of organized convection over various regions of land and ocean?
(2) Where do convective lines occur more often, over land or over ocean? Where do near-circular MCSs occur more often? What are the properties of these different-shaped regions of organized convection over different regions?

In the following sections, first the radar-defined precipitation features (RPFs) are identified from snapshots of contiguous precipitating regions indicated by the TRMM PR. Then, the convective features in each RPF are identified with the contiguous convective regions. The properties of these convective features, including their horizontal “shapes” and their associated stratiform precipitation, are summarized. The global distributions of the population and the properties of those convective features with large area, especially those with a line shape, are discussed.

2. Data and Methodology

Using the Version 7 TRMM PR rainfall retrieval product [Iguchi et al., 2000, 2009] during 1998–2011, PR precipitation features (RPFs) are identified by grouping the contiguous pixels with near-surface precipitation. After recording the general information of RPF size (total pixel numbers), mean rain rate, convective rain contribution, etc., the convective intensity proxies for each PF, such as minimum 85 GHz polarization corrected temperature (PCT) [Spencer et al., 1989] estimated from TRMM Microwave Imager observed radiance, the maximum heights of PR 30 and 40 dBZ, and flash counts observed by the TRMM Lightning Imaging Sensor for each RPF, are analyzed. Additional information on the RPF database and its uses can be found in Liu et al. [2008]. Using similar methodology, the convective features (CFs) are identified by grouping the contiguous pixels with convective precipitation that are categorized by the PR rain type algorithm [Awaka et al., 1998, 2009]. Then, the properties of each CF similar to the properties of RPFs are summarized. The environmental soundings for each one of these CFs are obtained by interpolation from 1.5° × 1.5°, 6 h interval ERA-Interim reanalysis data as described by Dee et al. [2011]. For each CF, its unique parent RPF is assigned. However, each RPF could have multiple component CFs.

To describe the horizontal structure of the CFs and RPFs, ellipse fittings of the areas of CFs and RPFs have been
performed with the methodology similar to that used by Nesbitt et al. [2006]. The major and minor axes and the orientations of the major axis of the ellipses are calculated. Four examples of MCSs observed by TRMM are shown in Figure 1: A convective line associated with cold front over the South Indian Ocean (Figure 1a), a shallow line-shaped precipitation system over the tropical east Pacific (Figure 1b), a typical squall line over West Africa with a leading convective line and a trailing stratiform precipitation region (Figure 1c), and a near-circular convective system over Oklahoma, U.S. (Figure 1d). The fitted ellipses and the major and minor axes of the CFs of these MCSs are shown. By using the ratio of the minor and major axes ($R_{\text{Minor/Major}}$), the shape of a CF can be roughly described as a line (small value of $R_{\text{Minor/Major}}$ as in Figures 1a–1c) or close to a circle ($R_{\text{Minor/Major}}$ close to 1 as in Figure 1d). This methodology works only when the convective lines have simple structures. The ellipse fit could be misleading when there is a complex of multiple convective lines.

3. Global Distribution of Organized Convection

Because the width of the PR swath is only 215 km pre and 245 km post satellite orbit boost in August 2001, there are many CFs located at the edges of the swaths. The categorization of the shape of a CF may be misleading by using an ellipse fitting only part of the CF within the PR swath (e.g., Figure 1b). Nesbitt et al. [2006] discussed this edge effect and found that this effect is not intolerable for MCSs. To minimize noise, only the RPFs and CFs with at least 4 pixels (about 80 km$^2$) are used in the discussion of the sizes of the convective systems in section 3.1, then those with large area and different shapes are investigated further in the rest of the study.

![Figure 1](image-url)
RPFs and CFs are similar to and consistent with past studies [Nesbitt et al., 2000; Liu et al. 2008] and are not shown here. We mainly focus on describing the properties of the CFs with large areas in the following sections.

### 3.1. Horizontal Extent

**[11]** First, to demonstrate the importance of organized convection, the properties of CFs are examined by two-dimensional histograms of the CFs over land and ocean as

<table>
<thead>
<tr>
<th>Fraction over land or ocean</th>
<th>Convective Features</th>
<th>Precipitation Features</th>
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<tbody>
<tr>
<td>(CFs) ~21 million</td>
<td>(RPFs) ~28 million</td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>Land</td>
<td>Ocean</td>
</tr>
<tr>
<td>17.7 million</td>
<td>3.7 million</td>
<td>22.8 million</td>
</tr>
<tr>
<td>83%</td>
<td>17%</td>
<td>80%</td>
</tr>
<tr>
<td>With area &gt; 1000 km²</td>
<td>214,885</td>
<td>126,286</td>
</tr>
<tr>
<td>1.2%</td>
<td>3.4%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Fraction of regions &gt; 1000 km and $R_{\text{minor/major}} &lt; 0.2$</td>
<td>32,526</td>
<td>5,694</td>
</tr>
<tr>
<td>15.1%</td>
<td>4.5%</td>
<td>6.9%</td>
</tr>
<tr>
<td>Fraction of regions &gt; 1000 km and $R_{\text{minor/major}} &gt; 0.6$</td>
<td>31,144</td>
<td>26,495</td>
</tr>
<tr>
<td>14.5%</td>
<td>21.0%</td>
<td>21.9%</td>
</tr>
</tbody>
</table>

| With area > 1000 km²        | 214,885            | 126,286                | 1,622,861             | 641,138                |
| Fraction of regions > 1000 km and $R_{\text{minor/major}} < 0.2$ | 32,526            | 5,694                  | 112,395               | 19,197                 |
| Fraction of regions > 1000 km and $R_{\text{minor/major}} > 0.6$ | 31,144            | 26,495                 | 354,962               | 180,838                |

**Table 1.** Population of the Convective Features (CFs) and Precipitation Features (RPFs) With at Least 4 PR Pixels (>~80 km²) During 1998–2011 Over 36°S–36°N and Those With Area > 1000 km² and Different Morphologies

**Footnote:** Here $R_{\text{minor/major}}$ is the ratio between the minor and major axis of the ellipse fitted over a convective or precipitation feature. High $R_{\text{minor/major}}$ means feature with a more circular shape, low $R_{\text{minor/major}}$ means feature with a clear line shape.

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**Figure 2.** (a) Cumulative two-dimensional histogram of the CFs over ocean as the function of their area and the maximum height of 30 dBZ. (b) Same as Figure 2a but for the CFs over land. (c) Cumulative two-dimensional histogram of the precipitation features (RPFs) over ocean as the function of their area with convective precipitation and the area fraction of stratiform precipitation. (d) Same as Figure 2c but for the RPFs over land.
a function of size and the maximum height of the 30 dBZ echo (Figures 2a and 2b). In general, CFs over land have larger sizes and higher 30 dBZ echo heights than those over the ocean. CFs with larger areas have stronger convective intensity with a higher 30 dBZ echo top height, more so over land (Figure 2b) than over ocean (Figure 2a). It is interesting that over both land and ocean there are many CFs with a large horizontal extent but a relatively low 30 dBZ echo top, more of which are over the ocean than over land. These CFs are relatively shallow and will be discussed further in section 3.4.

[12] The stratiform precipitation in the MCSs has a top-heavy latent heating vertical structure that is different from that of the convective region [Houze, 1989]. Organized convection is often accompanied with a large area of stratiform precipitation. To demonstrate the relationship between the stratiform region and the convective region quantitatively, two-dimensional histograms of RPFs over land and ocean as a function of area of the convective region and the fraction of stratiform region are shown in Figures 2c and 2d. Over the ocean, RPFs with a convection area smaller than 1000 km² have large variations in the fraction of stratiform area (Figure 2c). However, when convective areas are greater than 1000 km², the fraction of stratiform area increases with the area of the convective region. This is somewhat shown from TOGA COARE aircraft radar data as well, but with much fewer samples [Yuter and Houze, 1998]. This is reasonable, because the lifetimes of individual convective cells are short, but when they persist for a period of many hours they may form a large convective region, gradually increasing the size of the stratiform precipitation region generated from the dead or dying cells. Organized convection with a larger extent has taken longer to develop [Chen and Houze, 1997], and therefore is often associated with a larger stratiform region.

[13] Over the ocean, there are some RPFs with convective area up to 1500 km² and without stratiform precipitation. They are shallow organized features and will be discussed further in section 3.4. Over land, the existence of stratiform precipitation is guaranteed when the convective region is greater than 1000 km². Stratiform fraction increases once the convective region area is greater than 1000 km² over both land and ocean (Figures 2c and 2d). Convective regions over land between 1000² km and 2000 km² have stratiform regions that are slightly smaller with values of convective area/stratiform area fraction from 0.2 to 0.6 than those over ocean (0.4-0.8). We are mainly interested in convection organized on the mesoscale, which may be considered as at least small MCSs. Therefore, only the CFs with size greater than 1000 km² are discussed further in the rest of the paper.

3.2. Global Distribution and Morphology

[14] The numbers of CFs and RPFs with area > 1000 km² are listed in Table 1. There is a relatively lower fraction of CFs with large size over ocean than over land. This is due to the abundance of small isolated convective warm rainfall areas over the ocean [Schumacher and Houze, 2003a, 2003b; Liu and Zipser, 2009]. The global distribution of the population of RPFs and CFs with area > 1000 km² and their contributions to the total rainfall and convective rainfall are shown in Figure 3. There are more large RPFs over the tropics (Figure 3a) and they predominantly contribute to the local precipitation over rainy regions (Figure 3b). This is consistent with the existing literature [Laing and Fritsch, 1997; Nesbitt et al., 2000, 2006; Liu, 2011]. In contrast to the evenly distributed large RPFs over both land and ocean, there are more large CFs over land than over ocean (Figure 3c). Specifically, a larger proportion of convective rainfall is from organized convection (large CFs) over land than over ocean (Figure 3d).

Over certain land regions, the convective rainfall is predominantly from organized convection, including Central Africa and the Sahel, Argentina, southeast U.S., and Pakistan. These regions are also known for the most intense storms on Earth [Zipser et al., 2006]. However, there are many other land regions with a large population of convective features but with a much smaller percentage of their convective rainfall from large CFs, e.g., Amazon, Panama, and most of the maritime continent (Indonesia and vicinity).

[15] The relationships between the morphologies of the CFs and RPFs and their sizes are shown in Figure 4 with two-dimensional histograms of CFs and RPFs over land and ocean as a function of their sizes and the ratios between minor and major axis (RMinor/Major). Consistent with past literature [e.g., Nesbitt et al., 2000; Liu, 2011], precipitation systems tend to be larger over the ocean than over land (Figure 4a). However, organized convective regions (CFs) tend to be larger over land than over the ocean (Figure 4b).

[16] Both RPFs and CFs tend to be more circular with higher values of RMinor/Major over land than over the ocean (Table 1 and Figures 4a and 4b). This leads to higher fractions of CFs and RPFs with RMinor/Major > 0.6 over land than over ocean (Table 1). There are more line shaped CFs and RPFs over ocean (Figures 4a and 4b). The fractions of RPFs and CFs with RMinor/Major < 0.2 are 2-3 times larger over the ocean than over land (Table 1). In other words, it would be much easier to find a well-organized convective line over the ocean than over land. Houze and Cheng [1977] and Cetrone and Houze [2006] found that a majority (83%) of radar echoes could be assigned an orientation during GATE and KWAJEX field campaigns. This is further confirmed by the global distribution of populations of the circular-shaped and line-shaped CFs and RPFs in Figure 5.

[17] The global distribution of near-circularly shaped CFs and RPFs in Figures 5a and 5c is close to that of the large CFs and RPFs in Figures 3a and 3c, except with more over land than over the ocean. In contrast, more of the line-shaped CFs and RPFs are found over the ocean than over land (Figures 5b and 5d). Over the ocean, there are more line-shaped CFs and RPFs over the subtropics than the tropics, especially in the lee of continents. A lot of line-shaped CFs and RPFs in the subtropics are probably associated with frontal systems, especially during the winter and spring. Over tropical oceans, more line shaped CFs and RPFs are found over the Atlantic and east Pacific than over the west Pacific. The tropical Atlantic has the highest occurrence of line-shaped CFs and RPFs in tropics. We speculate that stronger horizontal temperature gradient of Intertropical Convergence Zone (ITCZ) and organized confluence at low levels over the east Pacific and Atlantic [Back and Bretherton 2009; Yokoyama and Takayabu, 2012] probably is one factor for more line shaped systems over these regions. Over land, organized convective lines occur more frequently over the southeast U.S., Bangladesh, and Panana regions than anywhere else in the tropics and subtropics (Figure 5b). Later, we shall show
Figure 3.  (a) Distribution of the population of the precipitation features (RPFs) with area > 1000 km². The distribution is created for 2° × 2° boxes and the values in the panel add up to 100%. The sample biases have been removed by using the number of the pixels sampled in each box. (b) Fraction of the rainfall contributed from the RPFs with area > 1000 km² in each 2° × 2° box. (c) Same as Figure 3a but for population of the convective features (CFs) with area > 1000 km². (d) Fraction of the convective rainfall from the CFs with area > 1000 km² in each 2° × 2° box.

Figure 4. (a) Cumulative two-dimensional histogram of the RPFs over land (contours) and ocean (color fills) as the function of the area and the $\frac{\text{Minor axis}}{\text{Major axis}}$. (b) Same as Figure 4a but for CFs. The histograms are created by using the samples of CFs and RPFs with area > 400 km².
seasonal distributions of convective lines that can be associated with known regional weather systems.

### 3.3. Convective Intensity

[18] The relationship between convective intensity and the shapes of organized convective systems is examined in Figure 6 with a two-dimensional histogram of large CFs as a function of \( R_{\text{Minor/Major}} \) and convective intensity proxies including the maximum height of 20 and 30 dBZ echoes, minimum 37 GHz PCT and the lightning flash rate. Consistent with the well known convective intensity difference over land and ocean, organized convection over land is stronger than that over the ocean with higher 20 and 30 dBZ echo top heights, colder 37 GHz brightness temperatures and higher flash rates in large CFs (Figures 6a–6d and 7a–7b). The strongest convection occurs more often in neither circular-shaped nor line-shaped CFs, but in CFs with \( R_{\text{Minor/Major}} \) around 0.3–0.4, which is the most commonly shaped CF (Figure 4a). In fact, convective lines often have relatively weaker convective intensity with lower 30 dBZ echo tops (Figure 7a) and warmer 37 GHz brightness temperatures (Figure 7b). Simulation studies [e.g., Rotunno et al., 1988] suggest that strong low level wind shear would lead to bow shaped convective structure, which are more convectively intense than “ordinary” convective lines often observed under weak and moderate low level wind shear. Our use of 0.2 to define a linear aspect ratio is very restrictive and likely excludes the bow-shaped convection. Over land, almost all large CFs have 20 dBZ echo tops reaching 7 km and with 30 dBZ above the freezing level (contours in Figures 6b and 6a). However, there are two groups of large CFs with different convective intensities over the ocean. One group has 20 dBZ echo top heights below 4 km and warm 37 GHz PCTs (Figures 6a–6c).

### 3.4. Shallow but Organized Convection

[19] Liu and Zipser [2009] have reported some examples of contiguous warm rainfall with large areas. Figure 6 confirms that such large but shallow convective systems are not rare. The global distribution of these organized, mostly warm rain systems in different seasons are shown in Figure 8. Almost all of this shallow organized convection occurs over the ocean and coastal regions. In the tropical ITCZ region, the shallow organized convection is mostly

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**Figure 5.** (a) Distribution of the population of large CFs with area > 1000 km\(^2\) and with a near-circular shape (\( R_{\text{Minor/Major}} > 0.6 \)). (b) Distribution of the population of large convective lines (CFs with \( R_{\text{Minor/Major}} \) < 0.2 and area > 1000 km\(^2\)). (c) Distribution of the population of the RPFs with area > 1000 km\(^2\) and with a near-circular shape (\( R_{\text{Minor/Major}} > 0.6 \)). (d) Distribution of the population of the RPFs with area 1000 km\(^2\) and with a line shape (\( R_{\text{Minor/Major}} < 0.2 \)). The distributions are created in 2° × 2° boxes and the values in each panel add up to 100%. The sample biases have been removed by using the number of the pixels sampled in each box.
convective feature > 1000 km$^2$

**Figure 6.** (a) Cumulative two-dimensional histogram of the convective features (CFs) with area 1000 km$^2$ over ocean (color fill) and land (contours) as the function of the maximum height of 30 dBZ and $R_{\text{Minor/Major}}$. (b) Same as Figure 6a but as the function of the maximum height of 20 dBZ and $R_{\text{Minor/Major}}$. (c) Same as Figure 6a but as the function of the minimum 37 GHz PCT [Spencer et al., 1989] and $R_{\text{Minor/Major}}$. (d) Cumulative two-dimensional histogram of the CFs with area > 1000 km$^2$ and at least one flash as the function of the flash rate and $R_{\text{Minor/Major}}$.

**Figure 7.** (a) Histogram of the large convective features with ice (CFs with 20 dBZ echo top > 5 km and area > 1000 km$^2$) with different shapes (different $R_{\text{Minor/Major}}$ values) over tropical land (red) and ocean (blue) as a function of the maximum height of 30 dBZ. (b) Same as Figure 7a but as the function of the minimum 37 GHz PCT. Note that the samples of shallow convection over ocean are excluded by requiring 20 dBZ echo top > 5 km.
confined to the east Pacific, especially in September-February (Figures 8a and 8d). This is most likely closely related to the unique shallow circulation over the region [Zhang et al., 2004; Yokoyama and Takayabu, 2012]. Shallow organized convection can also be found over the tropical-subtropical transition zones with large-scale subsidence, such as over the east South Pacific Convergence Zone (SPCZ) and South Indian Ocean in June-November (Figures 8c and 8d) and North Pacific and Northwest Atlantic in December-May (Figures 8a and 8b). It is not uncommon to find a large area of shallow convection near certain coastal regions, which are likely generated by the forced lifting of moist air in the trade winds over the east coasts of Brazil and Madagascar and the west coast of India in June-August and the east coast of Panama in December-February. It is worth noting that the shallow warm rainfall only contributes a small fraction of the total precipitation globally [Schumacher and Houze, 2003a, 2003b; Liu and Zipser, 2009]. The latent heating release in shallow convection is mainly in the lower troposphere and may be closely related to the shallow circulations in regions such as the east Pacific ITCZ [Zhang et al., 2004; Yokoyama and Takayabu, 2012].

4. Convective Lines

[20] There are many model simulation studies of quasi-two-dimensional squall lines because they are easily described in a two-dimensional framework [e.g., Rotunno et al., 1988; Weisman and Rotunno, 2004; Parker and Johnson, 2004]. In the real world, squall lines are observed frequently, and in agreement with many studies, are often associated with moderate or greater low-level wind shear. LeMone et al. [1998] summarized the convective lines during TOGA-COARE finding that convection prefers orientation parallel to the low level wind shear if it is sufficiently strong, but otherwise may line up parallel to midlevel shear. Johnson et al.’s [2005] results added the factor of humidity in the mid troposphere with the more complicated structures.
observed in South China Sea Monsoon Experiment [Lau et al., 2000]. The convective lines defined in this paper probably include many squall lines, but our definition is quite general, so it likely includes a variety of features that may be rather different from squall lines, such as cold fronts, shallow convective lines, and terrain forced convective lines over mountain slopes. In this section, it is appropriate to examine the regional and seasonal variation of the occurrence of these satellite-defined convective lines, and their properties.

4.1. Global Distribution and Orientation

[21] The locations and the orientations of large convective lines in different seasons are shown with CFs with $R_{\text{Minor/Major}} < 0.2$ and area $> 1000 \text{ km}^2$ in Figure 9. The literature on squall lines emphasizes low level wind shear, because it is capable of encouraging self-organization of deep convection, once initiated, often in the form of a shear-perpendicular line that also marks the leading edge of a cold pool, or gust front.

[22] However, lines of deep convection are also quite common along air mass boundaries such as fronts and dry lines, and in fact along almost any linearly oriented zone of low-level convergence, regardless of the specific forcing mechanism, if sufficient moisture and convective instability exists.

[23] In general, the locations of the convective lines in Figure 9 are consistent with the regions and seasons where linear features might be expected, although there are a few surprises. Over both land and ocean, strong linear forcing along baroclinic zones, often cold fronts, is a plausible explanation for the frequent occurrence of lines observed especially during the cooler seasons in the subtropics. The Mei-Yu fronts over China in MAM, and the Bai-Yu fronts

**Figure 9.** Locations of convective lines (CFs with $R_{\text{Minor/Major}} < 0.2$ and area $> 1000 \text{ km}^2$) in different seasons. The short lines show the orientation of the convective lines, and the thickness and the length of the short lines are proportional of the minor and major axes of the convective lines. Note that the sample biases are not removed here, therefore the large population of convective lines over the subtropics is partially due to the larger number samples by the TRMM PR there.
over Japan in JJA, are often formed along lines with weak temperature gradients but strong moisture gradients [e.g., Chen, 2004]. Some of the lines over the south Central U.S. seen in MAM may be along dry lines [e.g., Weckwerth and Parsons, 2006], although their orientation (Figure 9b) is often more east-west than dry lines tend to be. Lines of forcing can be from low level winds impinging on coastlines and high terrain, e.g., trade winds on the east coasts of Panama and Madagascar, and the west coasts of India (JJA) and parts of Malaysia and Indonesia (all seasons). Forcing can be also from elongated mountains such as those at the south slope of the Himalayas (MAM and JJA) and the east slope of the Andes, although apparently less frequently in all of these locations than might be expected. The West African Sahel in JJA is well known for strong squall lines, often oriented N-S [e.g., Laffore and Moncrieff, 1989; Rowell and Milford, 1993; Cetrone and Houze, 2011], but rather few are found by this definition, especially north of 10°N.

[24] Over subtropical oceans as well as over land, low level convergence can often result from forcing along baroclinic zones, including cold fronts, but as is well known, convective lines are often found over warm ocean currents and the strong temperature gradients along their poleward boundaries. For example, there are more convective lines over the West Atlantic along the Gulf Stream [Doyle and Warner 1993], over the west Pacific along the Kuroshio Current [Kondo, 1976], and over the West Indian Ocean along the Agulhas Current [Rouault et al., 2002].

[25] Over the tropics, there is a rough separation of different line orientations at the north and south sides of the ITCZ. Note that many convective lines are aligned east-west with the tropical Atlantic and the east Pacific ITCZ, consistent with the ocean currents and east-west-oriented surface temperature gradients in these regions. Houze and Cheng [1977] and Cetrone and Houze [2006] found that the lines of radar echoes are strongly related to the low level wind field during the GATE and KWAJEX field campaign. The low level confluence caused by temperature gradients over these regions likely play an important role in the formation of these lines [e.g., Yokoyama and Takayabu, 2012]. The histograms of the orientations of the convective lines over land and ocean are shown in Figure 10. Consistent with Figure 9, there is a clean separation of the orientations of convective lines in the northern and the southern subtropics in Figure 10. It is interesting that the convective lines over subtropical oceans are tilted farther from east-west than those over subtropical land.

[26] Using the same methodology, the orientations of line shaped precipitation regions are analyzed with the RPFs. Because of the complicated horizontal structure of the stratiform precipitation regions, possibly due to the mesoscale circulation in the MCSs, the orientations of the precipitation lines are not as clearly aligned as the convective lines (Figures are not shown). Note that the impact of the edge cutting due to the narrow swath of the PR could lead to bias in line orientation, but in either direction, and any such bias is not obvious from the orientations of the convective lines in Figure 9. This adds some confidence in the results shown here.

4.2. Seasonal Variation

[27] It is difficult to compare the population of the convective lines in subtropics and tropics directly in Figure 9 because the sampling biases of TRMM lead to more convective lines observed over subtropics. After removing the sampling bias, the zonal and seasonal variation of the large convective regions over land and ocean area shown in Figures 11a–11b as a two-dimensional histogram of CFs with area greater than 1000 km². Similarly, the zonal and seasonal variation of the large convective lines over land and ocean are shown in Figures 11c–11d as two-dimensional histograms of CFs with $R_{\text{Minor/Major}} < 0.2$ and area 1000 km² as a function of latitude and month. Over the subtropical oceans, most of the convective lines occur in winter (Figure 11c). However, over subtropical land, most of the convective lines occur in summer (Figure 11d). There are more convective lines over tropical land than subtropical land (Figure 11d). The proportions of large CFs in Figures 11a and 11b having line-shape are shown in Figures 11e–11f. A larger proportion of CFs have line-shapes over ocean (Figure 11e) than over land (Figure 11f). Higher fractions of line shaped CFs are found in the subtropics than tropics over both land and ocean. Over the subtropics, large CFs are more likely to have line shapes in winter than in summer (Figures 11e–11f), and are more likely associated with cold fronts (Figure 11f).

4.3. Extremely Large and Intense Events

[28] To demonstrate the regional variations of size and convective intensity of the large convective lines, CFs with $R_{\text{Minor/Major}} < 0.2$ and area > 1000 km² are categorized by their size and maximum height of the 40 dBZ echo. Then, the CFs’ locations are marked with different symbols representing their sizes and convective intensities in Figure 12. Consistent with the difference between the sizes of the convective regions over land and that over ocean in Figure 4a, the convective lines over land are also larger than those over ocean (Figure 12a). The largest convective lines over land are found over Central Africa, southeast U.S., and Argentina. The largest convective lines over ocean are

![Figure 10. Histogram of the orientations of large convective lines (CFs with $R_{\text{Minor/Major}} < 0.2$ and area > 1000 km²) over tropical and subtropical land and ocean. Note that the orientation is calculated from east-west ($0^\circ$).](image-url)
found over the subtropical Gulf Stream, Kuroshio, Brazil and Agulhas Currents, likely associated with frontal systems that are likely enhanced by the warm sea surface and sea surface temperature gradients. Consistent with the general land vs. ocean contrast in convective intensity, convective lines over land are more intense with higher maximum 40 dBZ echo tops than those over ocean (Figure 12b). The strongest convective lines are mainly over central Africa, Argentina and the southern US, regions already known to have very intense storms [Zipser et al., 2006].

5. Summary

[29] Using 14 years of TRMM observations, the regional variations of convective systems and their organization into
The largest and the strongest convective lines over the ocean tend to be more linear over the ocean than over land. Well-defined line shaped organized convection is more frequently observed over the ocean than over land.

(1) Precipitation systems tend to be larger over the ocean, but organized convective systems tend to be larger over land. With increasing area of organized convection, the areal fraction covered by stratiform precipitation region tends to be larger.

(2) Shallow organized convection is found over the ocean and some coastal regions. Within the ITCZ, the largest number of such shallow convective systems are found over the east Pacific.

(3) Organized convection tends to be more circular over land, but more linear over the ocean. Well-defined line shaped organized convection is more frequently observed over the ocean than over land.

(4) Line shaped organized convection tends to be weaker than that with a circular shape. Orientations of organized convective lines are consistent with frontal systems over the subtropics. Over the subtropics, organized convective lines are oriented closer to east-west over land than over ocean.

(5) A higher fraction of organized convection is line-shaped over the ocean than over land, in the subtropics than in the tropics, and during winter than during summer in the subtropics. However, most of the subtropical convective lines over land occur in summer.

(6) The largest and the strongest convective lines over the ocean are found in alignment with warm subtropical currents or their associated gradients.

[30] To fully understand these findings, better knowledge of the large-scale wind and thermodynamic environments of organized convection is required. Future study will focus on the relationships between the large-scale environments and the properties of organized convection after collocating the TRMM observations and the reanalysis data, especially on the relationship between wind shear and orientations of convective lines and its implications on the momentum transport.

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References
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