What Percentage of Western North Pacific Tropical Cyclones Form Within the Monsoon Trough?

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ABSTRACT

It is frequently stated that 70-80% of western north Pacific tropical cyclones form "within the monsoon trough", but without an objective definition of the term. Several definitions are tested here. When the monsoon trough (MT) is defined as the contiguous region where long-term (1988-2010) mean July-November 850 hPa relative vorticity is positive, 73% of all July-November tropical cyclones form within the MT. This percentage varies interannually, however, from as low as 50% to nearly 100%. The percentage correlates with the Niño 3.4 index, with more storms forming within the MT during warm periods. When the MT is defined instead using long-term monthly mean ζ_{850}, more than 80% of tropical cyclones form within the MT in all months except July and August, when more than 30% of storms form poleward of the MT. It is hypothesized that the known peak in the frequency of upper tropospheric midlatitude wave breaking in July and August is responsible.

It is argued that any long-term mean provides a suitable definition of the MT. Defining it on less than seasonal time scales, however, creates a lack of conceptual separation between the MT and other tropical disturbances such as the MJO, equatorial waves, and easterly waves. The term "monsoon trough" should represent a climatological feature that provides an asymmetric background state within which other disturbances evolve.

1. Introduction

Harr and Chan (2005) have noted that the monsoon trough of the western north Pacific exhibits dynamical and thermodynamical conditions favorable for tropical storm formation. Following Gray (1979) and McBride (1995), they noted that these factors include substantial values of mean lower-tropospheric relative vorticity, small vertical wind shear, high sea surface temperature (SST), and high midtropospheric relative humidity. A number of researchers have defined parameters that evaluate the climatological conditions for genesis (e.g., Gray 1979; Emanuel and Nolan 2004; Camargo et al. 2007). These studies show that the western north Pacific is broadly favorable for genesis, especially during the warm season. In previous review papers on tropical cyclogenesis, both Frank (1987) and McBride (1995) stated that 80% of western north Pacific tropical cyclones form within the monsoon trough (hereafter MT).

Lander (1994, 1996) and Holland (1995) have described significant movement and structural changes in the monsoon trough on weekly time scales. Harr and Wu (2011) argued that the monsoon trough evolves on daily, weekly, and monthly time scales, and these variations strongly influence the locations of tropical cyclogenesis. Ritchie and Holland (1999) defined the MT subjectively using daily gridded analyses and infrared satellite images. They found that 42% of tropical cyclones formed within the monsoon shear region (with easterlies to the north and westerlies to the south), while another 29% formed within easterly waves at the leading edge of the MT. This gave a total of 71% of storms within the MT (74% if monsoon gyres are considered part of the MT).

The papers above provided no objective, reproducible definition of the MT. This calls into question the percentage of tropical cyclones attributed to MT influence. Harr and Chan (2005) defined the MT geographically as the area encompassing 0-20°N and 110-150°E. Using this definition, 63% of TCs formed within the MT. However, Harr and Chan (2005) provided no physical reasoning for choosing this region. Wu et al. (2012) used mean relative vorticity averaged 5-20°N to define the zonal variation of the intensity of the MT. This choice did not allow the MT to exist beyond the specified latitude range.

To address the question in the title, it is necessary to formally define the areal extent of the MT. The *Glossary of Meteorology* (2000) defines an MT as "the line in a weather map showing the locations of relatively minimum sea level pressure in a monsoon region". This is not helpful for the purposes of this paper, given that not many tropical cyclones can form within a line! One goal of this work is to test multiple definitions of the MT and determine the percentage of tropical cyclones that form within it for each definition.

The recent literature has extensive descriptions of the important roles of the MJO and equatorial waves in tropical cyclogenesis (e.g., Liebmann et al. 1994; Maloney and Hartmann 2000; Dickinson and Molinari 2002; Frank and Roundy 2006; Bessafi and Wheeler 2006; Camargo et al. 2009; Schreck and Molinari 2011; Schreck et al. 2012; Ventrice et al. 2012). Schreck et al. (2012) found that, depending upon the criterion used, 80-95% of western north Pacific tropical cyclones form in direct association with the active MJO and/or the active regions of various equatorial waves. The second purpose of this paper is to address the need for a conceptual separation of these disturbances from the MT.

2. Definition of the MT

Several characteristics must be considered in formulating a definition of the MT. These include the variable to be used, the choice of spatial and temporal scales, and whether the MT is distinguished from the ITCZ. The MT has been defined previously using rainfall (e.g., Wang and

LinHo 2002) and relative vorticity (Wu et al. 2012). The magnitude of ambient cyclonic relative vorticity has been shown to be an important factor in tropical cyclogenesis (e.g., Gray 1979; McBride and Zehr 1981; Schumacher et al. 2009). Schumacher et al. (2009) developed an effective tropical cyclogenesis statistical prediction system using only three variables: climatology of genesis at the location; nearness to another tropical cyclone; and 850 hPa relative vorticity averaged over 8° by 8° latitude-longitude boxes. The lack of added value in their model for convective instability, convective intensity, and SST suggests that much of the information within those variables is contained in the relative vorticity. As a result, relative vorticity at 850 hPa from ERA Interim Analyses (Simmons et al. 2007) will be used to define the MT in this study. Relative vorticity at the surface was also examined and gave nearly identical results.

The analysis region will range from 122°E to the Date Line. This region begins just east of the Philippines; it omits the South China Sea in order to avoid the differing seasonality in tropical storm genesis between the two regions (e.g., Lee et al. 2006). During the 23-year period of interest, only 7 tropical cyclones formed between the Date Line and 150°W. As a result, the extension of the MT east of the Date Line that can occur during El Niño (e.g., Wu et al. 2012) will not be considered.

Traditionally the MT is defined as having westerlies on its equatorward side, while the ITCZ is defined as having confluent easterlies on each side (e.g., Fig. 3.4 from McBride 1995). In this study the ITCZ will be counted as part of the MT because the mean vorticity field will be seen to be continuous between the two (Fig. 1). When individual years are considered, only July-November means will be used, following Wu et al. (2012). This is consistent with the climatological jump in rainfall from west to east of the Philippines in July (Wu 2002). The sole difference among the MT definitions in this paper will relate to the temporal scale over which averaging is done.

3. Percentage of tropical cyclones forming within the MT

The first MT definition to be tested makes use of a climatological mean between 1988 and 2010. The MT is defined for each month as the contiguous region in the northwest Pacific in which the climatological mean 850 hPa relative vorticity is greater than zero. This definition accounts for the seasonal migration of the MT. Fig. 1 shows the results. Relative vorticity is shaded for positive values only. Tropical cyclone formation locations are shown (hurricane symbols) for the same period, obtained from the Joint Typhoon Warning Center. For all 12 months, the MT shows as a contiguous and unambiguous region of cyclonic relative vorticity east of the Philippines. In boreal winter it is largely confined to within 10° of the equator. During boreal spring, cross-equatorial flow develops at the western end and the MT shifts poleward. The meiyu (or baiu) front (e.g., Chen 2004) also develops during this period, but it lies near 30°N, physically separate from the cyclonic vorticity to the south, and will not be counted as part of the MT. The MT continues to shift poleward until September. Thereafter, the sequence reverses and the MT shifts equatorward. The largest mean vorticity maxima in the MT occur near the equator in boreal winter.

The percentage of tropical cyclones forming within the MT also experiences monthly variations. During the period from January to April, all storms during the 23-year period develop within this monthly mean climatological definition of the MT. With few exceptions, the same is true in May and June. During July and August, however, the number of tropical cyclone formations outside the MT grows dramatically, mostly on its poleward side. Thereafter the number of storms initiating outside the MT decreases to near zero by December.

Fig. 2 summarizes the percentage of tropical cyclones that form within the long-term monthly mean MT as a function of the time of year. This percentage exceeds 80% in every month except July and August, when it dips below 70%. Put differently, about twice as many tropical cyclones initiate outside the MT in July and August than in any other month. This result might relate to the July-August peak in midlatitude, upper-tropospheric Rossby wave breaking (Postel and Hitchman 1999). Tropical cyclones often develop in the subtropics associated with breaking waves (e.g., McTaggart-Cowan et al. 2008; Davis and Bosart 2006). In addition, large subtropical gyres (Lander 1994) are often directly tied to extratropical wavebreaking (Molinari and Vollaro 2012), and tropical cyclones form on the edges and within such gyres, often at higher latitudes. It is hypothesized that the peak in midsummer wavebreaking is responsible for the higher percentage of tropical cyclones developing poleward of the climatological monthly mean MT in July and August.

If the vorticity criterion is increased from zero to 1×10^{-6} s^{-1}, the MT area decreases slightly and the percentage of tropical cyclones forming within the MT decreases by 2-9%, depending upon the month. The general conclusions above remain unchanged.

Fig. 3 introduces a second definition of the MT: the contiguous region in which the long-term (1988-2010) mean July-November ζ_{850} is positive. Also shown are tropical cyclone formation locations for the same period. Using this MT definition, 73% of all July-November western north Pacific tropical cyclones arise within the MT. Once again most of the exceptions lie poleward of the MT.

One striking aspect of Fig. 3 is the relatively small percentage of storms that form within what might be called the traditional monsoon trough, i.e., the region of cyclonic vorticity exhibiting westerlies to its south. This region lies west of about 145°E in Fig. 3. If the ITCZ were not included in the MT definition, the percentage of storms forming within the MT falls to 41%. A comparable reduction exists for each individual month (see Fig. 1).

All ENSO states are combined in the MT definitions used in Figs. 1 and 3, thereby obscuring any differences in MT behavior between El Niño and La Niña (e.g., Wang and Chan 2002; Camargo et al. 2007; Wu et al. 2012). Fig. 4 shows two curves. The first (dashed) is the percentage of tropical cyclones each year that form within the long-term July-November mean MT shown in Fig. 3. The second curve (solid) introduces a third definition for the MT: the July-November mean contiguous region of cyclonic relative vorticity for each individual year. The percentage of tropical cyclones forming within the MT by each of these definitions displays similar dramatic interannual variations. The bold lower curve in Fig. 4 shows the July-November mean Niño 3.4 SST anomaly for each year. The linear correlation coefficient between the Niño3.4 index and the solid and dashed lines are 0.61 and 0.24, respectively, indicating a role for ENSO in the percentage of storms developing within the MT. The percentage of storms forming outside the climatological MT (Fig. 3) is almost double during negative Niño3.4 anomalies (31%) versus positive (16%). This is consistent with the tendency for storms to form to the north and west during La Niña, and to the south and east during El Niño (Wang and Chan 2002; Kim et al. 2011).

The final MT definition is simply the mean ζ_{850} for each individual month within each year. This definition often produces non-contiguous regions of cyclonic vorticity, and the definition of the MT becomes uncertain. Fig. 5 shows one such example from August 1988. The MT existed in its climatological location (compare with Fig. 1h), but was much weaker and covered less area. No storms formed within that MT. A region of strong mean vorticity existed near 30°N, but this meiyu-type structure was almost certainly associated with baroclinic middle latitude dynamics (Chen 2004; Kosaka et al. 2011). There seems little sense in attributing the storm north of 30°N near 144°E in Fig. 5 as MT-induced. Use of such monthly mean vorticity values creates difficulty in defining a unique MT.

Individual monthly mean vorticity creates two additional difficulties. First, tropical cyclones produce maxima in mean vorticity when their tracks happen to cluster together, often at latitudes near or north of 30°N (not shown; see Molinari 2012). Such maxima clearly represent tropical cyclone track variations, not variations of the MT. Second and more importantly, a one-month mean MT definition represents the same time scale as the MJO, and the conceptual distinction between them is obscured.

Defining the MT on a daily basis, as is often done in operations, creates even more problems. The MT is then entangled with equatorial wave modes (e.g., Wheeler et al. 2000; Roundy and Frank 2004), easterly waves, and even tropical cyclones and mesoscale convective systems. These issues are addressed further in Section 4b.

The term "monsoon trough" appears frequently in the literature, but nearly always without a formal definition. The results of this paper show that the position and intensity of the MT can vary widely, even among reasonable choices. We believe that an objective, reproducible definition of the term should always be provided to facilitate communication among researchers and between research and operations.

4. Discussion

a. Percentage of storms within the MT

When the monsoon trough (MT) is defined as the contiguous region east of the Philippines in which long-term mean July-November 850 hPa relative vorticity is positive, 73% of all July-November tropical cyclones form within the MT (Fig. 3). This percentage varies interannually, however, from as few as 50% to 100% (Fig. 4). The percentage correlates with the Niño 3.4 index. During warm Niño 3.4 periods, a higher percentage of storms form within the MT (84%) than in cool periods (69%), consistent with the smaller number of high-latitude storms during El Niño (Wang and Chan 2002; Camargo et al. 2007).

When the MT definition is altered to the long-term monthly mean ζ_{850}, more than 80% of tropical cyclones form within the MT in all months except July and August (Fig. 2). During those two months, fewer than 70% of storms form within the MT, with almost all the rest to its poleward side (Fig. 1g,h). It is hypothesized that the known peak in the frequency of upper tropospheric midlatitude wave breaking in July and August (Postel and Hitchman 1999) is responsible for the large number of storms that form poleward of the long-term monthly mean MT in July and August. This view is consistent with the role of such breaking waves in tropical cyclogenesis found by Davis and Bosart (2006), McTaggart-Cowan et al. (2008) and Molinari and Vollaro (2012). The locations of clusters of storms forming north of the MT in Fig.1 in July and August is consistent with a maximum in trough-induced tropical cyclogenesis in boreal summer in the same region (Ron McTaggart-Cowan, personal communication, 2012).

b. What is the best definition for the monsoon trough?

The long-term mean monthly vorticity used in Fig. 1, and the multi-month long-term mean in Fig. 3, each provide a reasonable measure of the monsoon trough. The former includes the seasonal migration of the MT, while the latter serves as a single climatological measure of the MT extent during the warm season. The region of mean cyclonic vorticity for July-November of each individual year (solid line in Fig. 4) also provides useful information and allows for interannual comparisons and ENSO impacts, similar to those shown by Wu et al. (2012).

Difficulties arise for shorter period time averages. It was argued that defining the MT extent using the region of positive mean vorticity for individual one-month periods suffers from (i) non-contiguous vorticity regions, making definition of the MT ambiguous; (ii) too much influence from tropical cyclone tracks; and (iii) lack of separability from the MJO. As an example, if the MJO-induced westerlies and precipitation are north of their locations within the climatological MT, as suggested by comparing the results of Huang et al. (2011) to Fig. 1, should this be interpreted as a northward shift in the MT or an MJO-induced anomaly from the MT? If a strong midlatitude upper tropospheric trough propagates into the subtropics, does this produce a dynamically induced, southwest-northeast cloud band east of the trough axis (Molinari et al. 2012), or a "reverse monsoon trough" (Lander 1996)? Similar questions can be framed for Kelvin waves and equatorial Rossby waves. All these disturbances alter convection, zonal wind, and vorticity, but on varying time scales with varying propagation characteristics, and thus produce differing perturbations from the MT. We are wary of attributing all such time variations to changes in the structure and position of the MT such as those discussed by Lander (1996), Holland (1995), and Harr and Wu (2011).

It could be argued that the comments in the last paragraph relate only to terminology. For instance, the meiyu-type structure in Fig. 5 produced strong southwesterlies north of 20°N that extended poleward into a trough near 30°N (Lander 1996). Why is this trough not the monsoon trough, and what harm is done by calling it that? We believe that such usage blocks the development of synoptic models for the perturbations produced by various equatorial wave types, the MJO, and midlatitude trough penetrations into the subtropics. We favor the view of Frank and Roundy (2006), who describe the MT as a *climatologically* favorable region for tropical cyclone formation. This region then provides the background state within which other disturbances can grow (e.g., Sobel and Bretherton 1999; Kuo et al. 2001). This requires an MT definition that represents a multi-year mean or at the very least an average over a period several times that of the MJO, such as those presented in this paper.

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Figure Legends

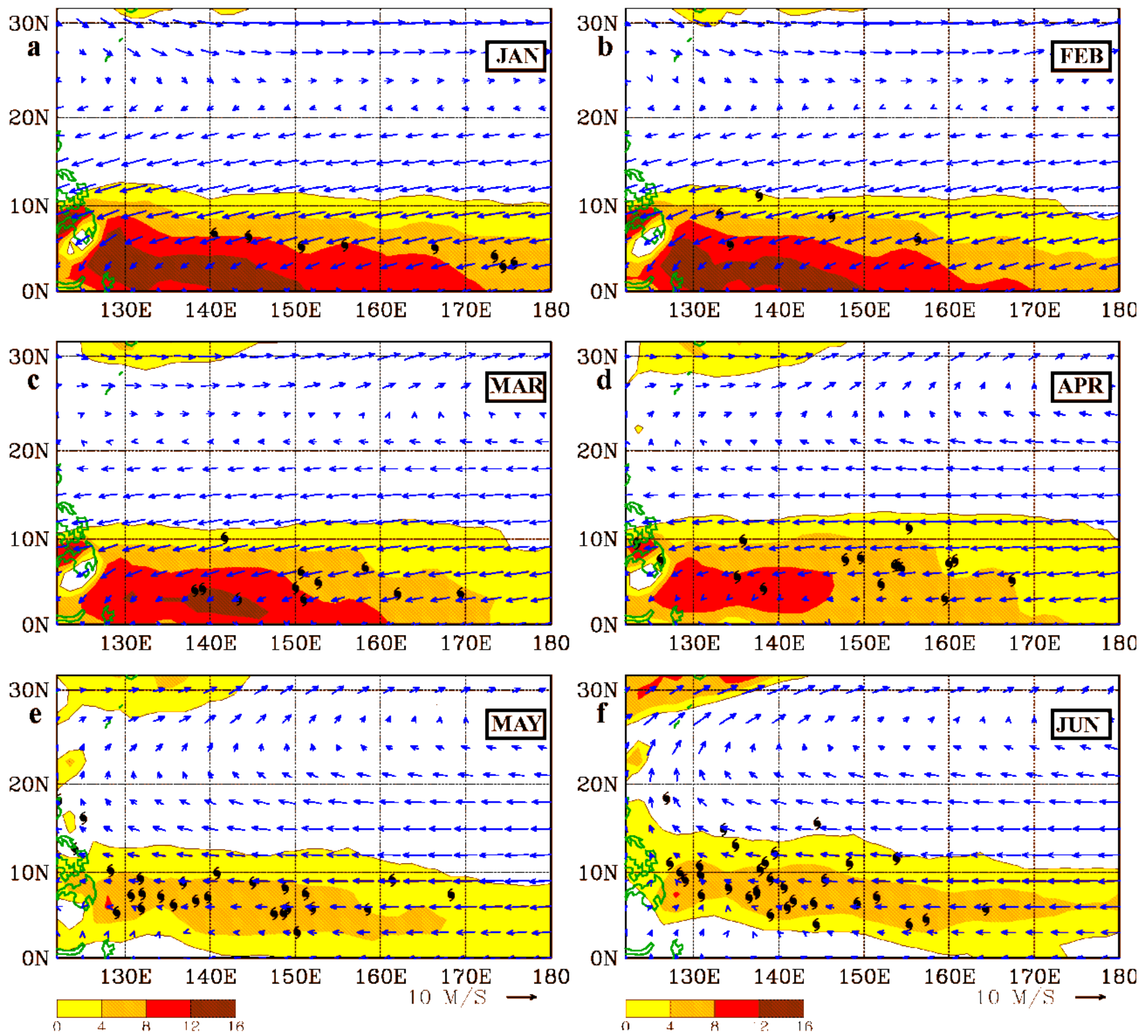
Figure 1. Long-term mean (1988-2010) northwest Pacific 850 hPa relative vorticity (10^{-6} s^{-1}, shaded for positive values only) and mean 850 hPa winds (vectors). Formation locations for tropical cyclones (symbols) for each month are obtained from the Joint Typhoon Warning Center. The first 6 panels cover January (panel a) to June (panel f) and the second set from July (panel g) to December (panel l).

Figure 2. Percentage of tropical cyclones forming within the long-term monthly mean monsoon trough positions shown in Fig. 1. The shading represents 70-80%.

Figure 3. As in Fig. 1, but the long-term mean 850 hPa relative vorticity and wind are averaged from July to November, and all July-November tropical cyclone formation locations are shown.

Figure 4. Dashed line: Percentage of tropical cyclones forming each year within the climatological July-November mean monsoon trough shown in Fig. 3. Top solid line: Percentage of tropical cyclones forming each year within the July-November mean positive ζ_{850} region for the same year. Bold solid line: Niño 3.4 index averaged July-November each year. Shading as in Fig. 2.

Figure 5. As in Fig. 1, but for the single month of August 1988.



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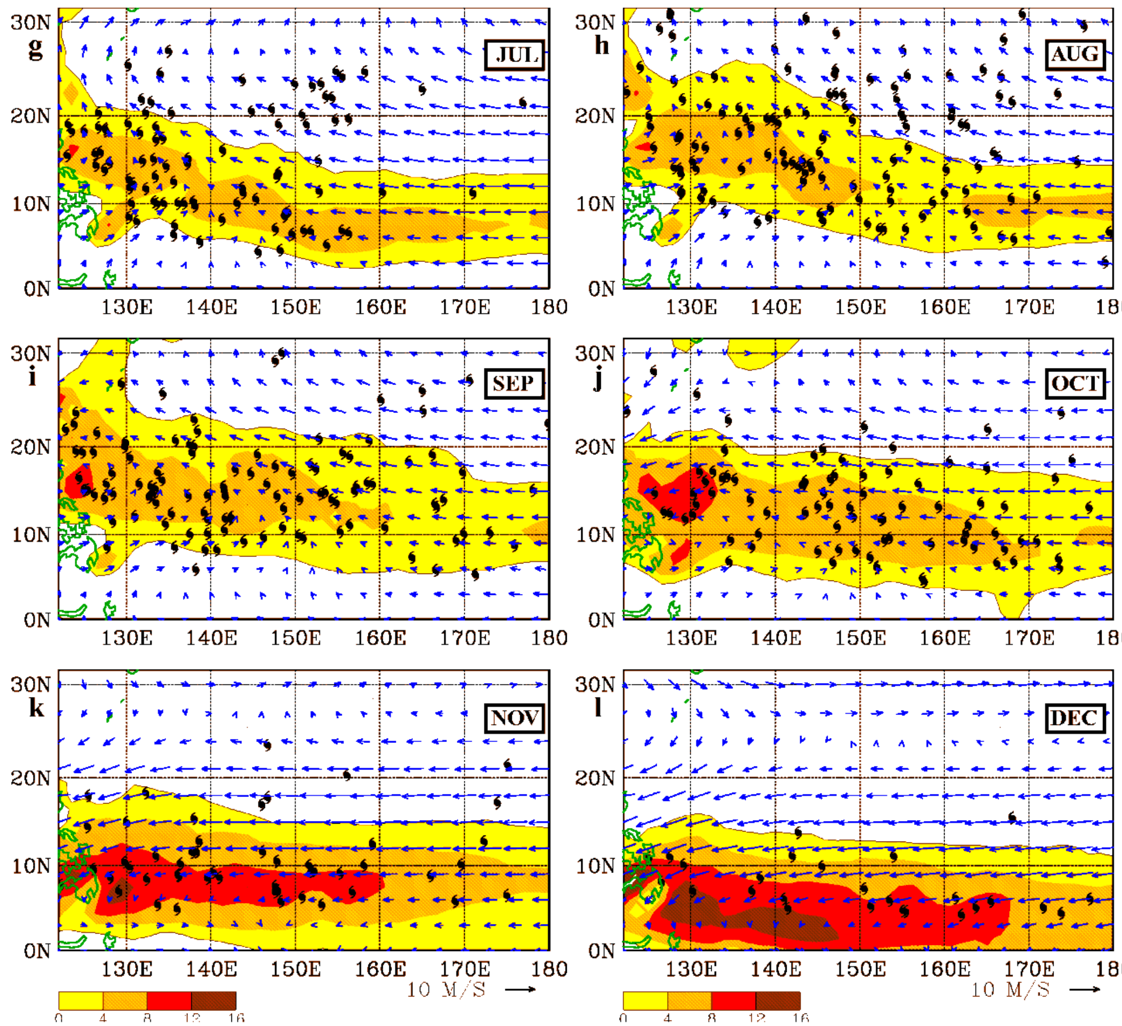
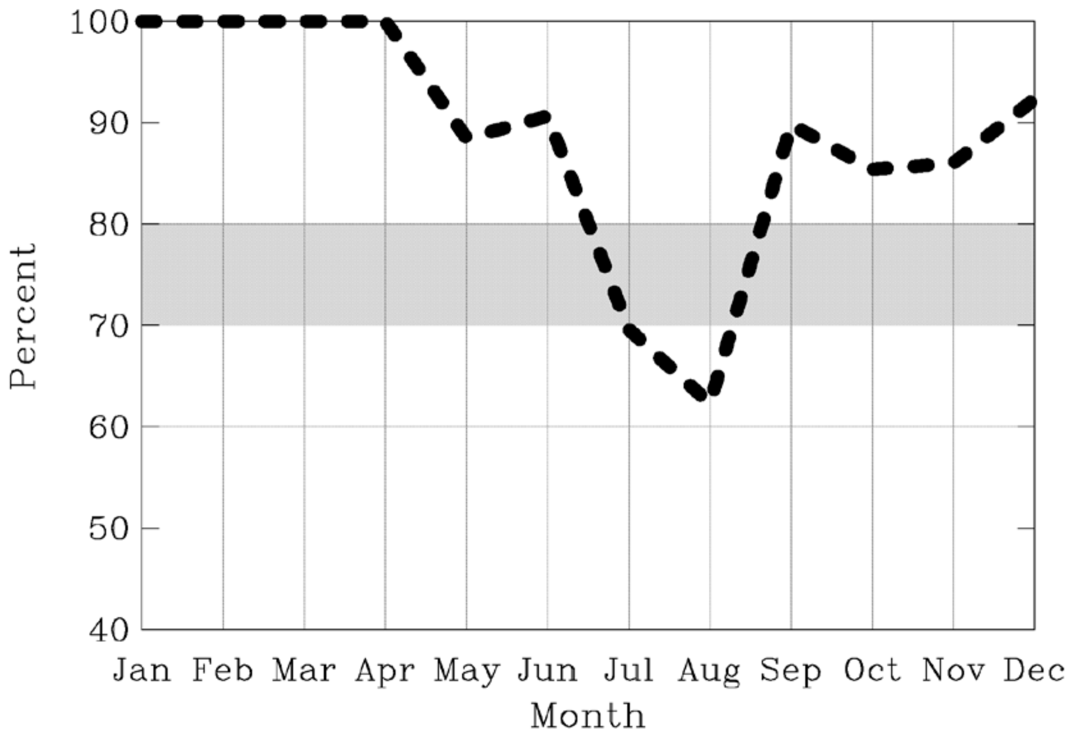


Figure 1. (continued)



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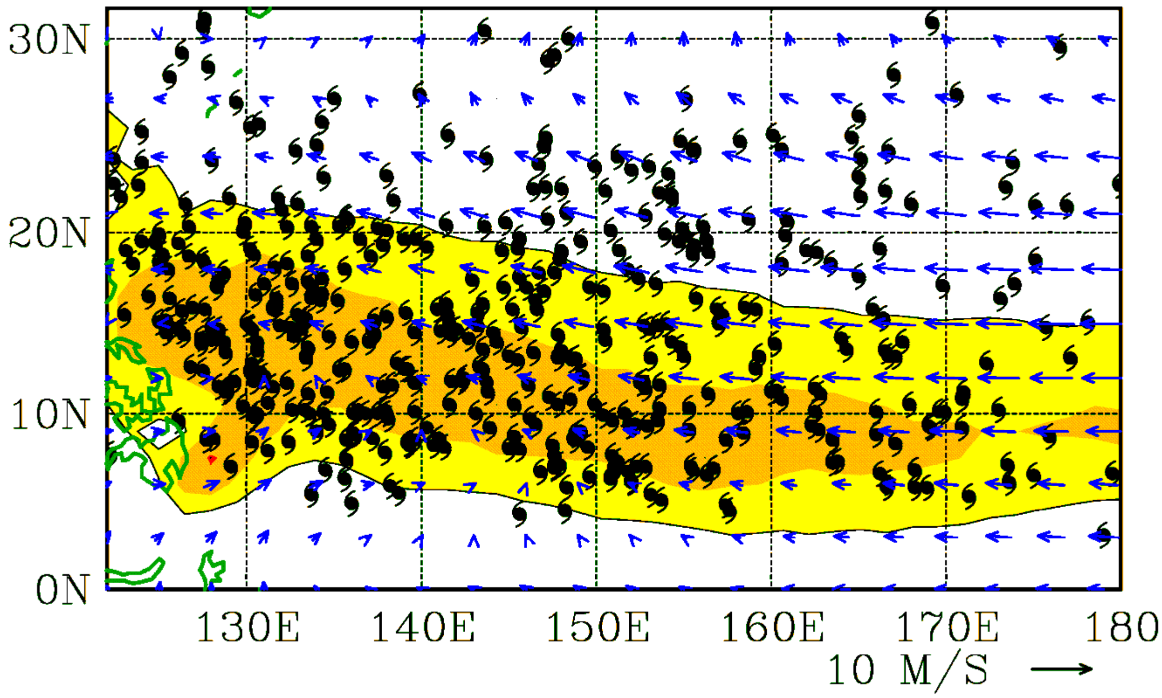

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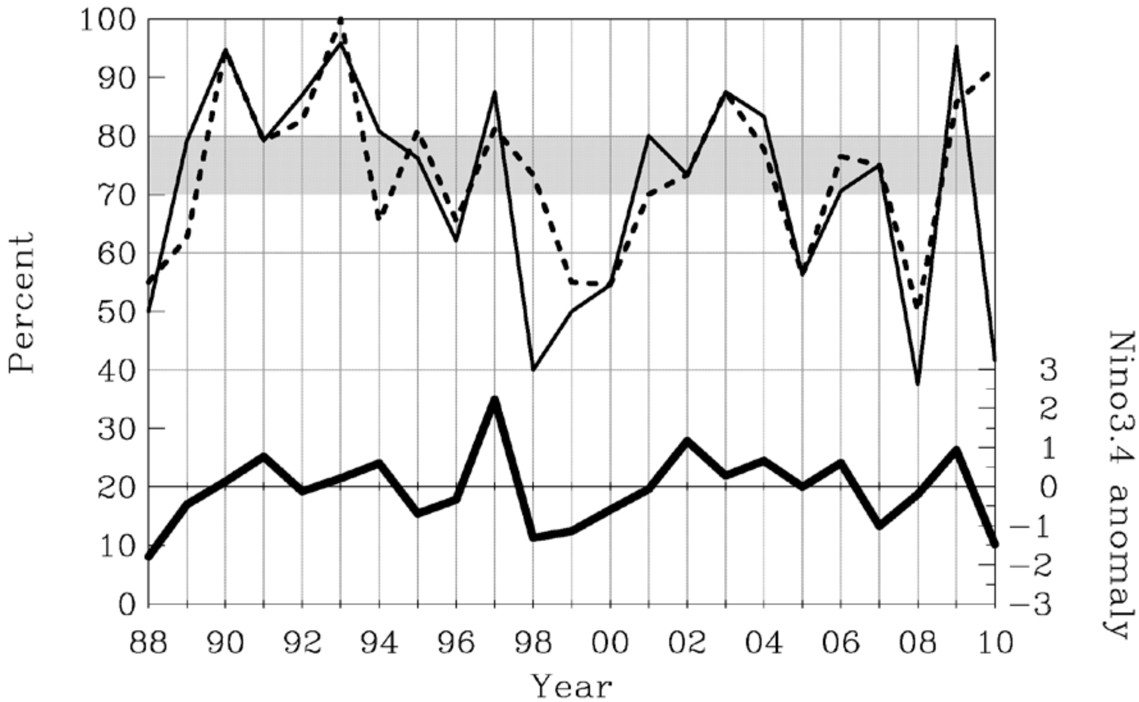

Figure 4. (dashed line) Percentage of tropical cyclones forming each year within the climatological July-November mean monsoon trough shown in Fig. 3. (top solid line) Percentage of tropical cyclones forming each year within the July-November mean positive ζ_{850} region for the same year. (bold solid line) Niño 3.4 index averaged July-November each year. Shading as in Fig. 2.

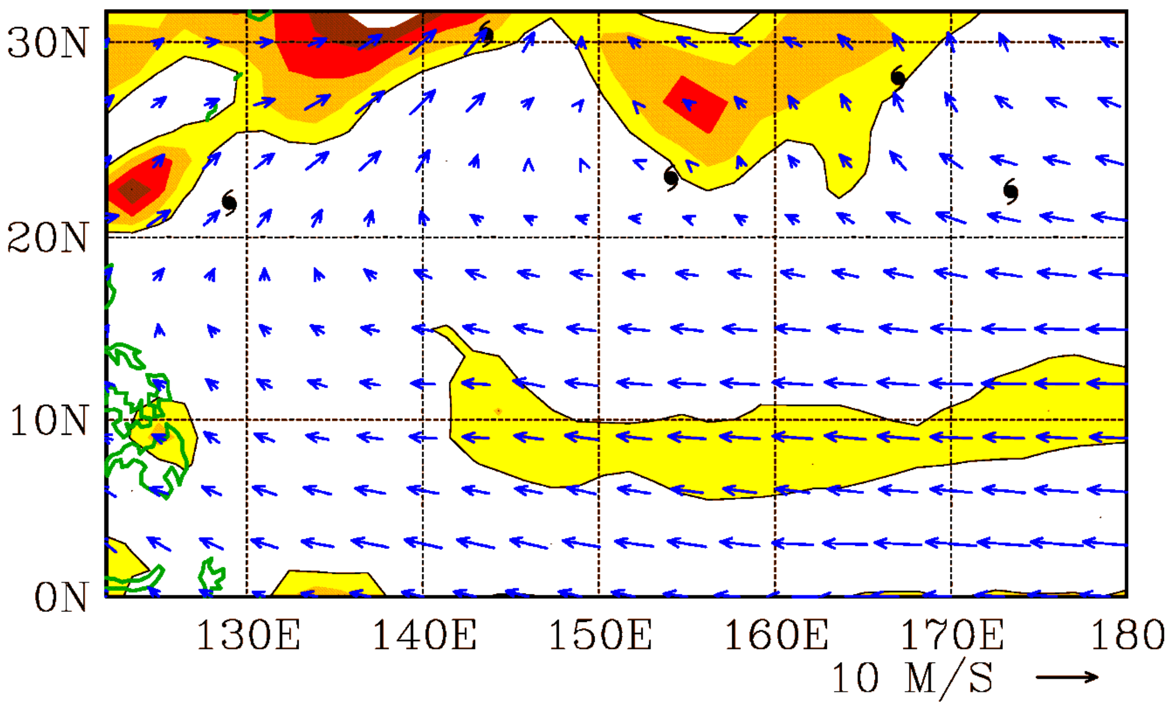

Figure 5. As in Fig. 1, but for the single month of August, 1988.