On the Relationship between Western Maritime Continent Monsoon Rainfall and ENSO during Northern Winter

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ABSTRACT

Several studies have reported that Indonesian rainfall is poorly correlated with El Niño–Southern Oscillation (ENSO) events during the northern winter wet monsoon season. This work studies the relationship between the Niño-3 (5°S–5°N, 150°–90°W) sea surface temperature (SST) and the Maritime Continent monsoon rainfall during 1979–2002. The study indicates that the correlations are mostly negative except in the vicinity of Sumatra and Malay Peninsula (SMP, including the western sections of Java and Borneo), where the correlations range from zero to weakly positive.

The monsoon rainfall during ENSO events is influenced by a pair of anomalous Walker cells and a low-level closed circulation centered near the Philippines. East of SMP, the rainfall is negatively correlated with Niño-3 SST. The anomalous low-level wind over the Indian Ocean west of SMP causes rainfall to also be correlated negatively with Niño-3 SST, but rainfall over SMP is sheltered from this effect because of the high mountains along its western coast. The anomalous cross-equatorial flow associated with ENSO also affects the rainfall over SMP and the area to its east differently. A variation of the cross-equatorial flow may also contribute to the SMP rainfall anomaly.

The result suggests that the previously reported low correlations between Indonesian monsoon rainfall and ENSO are due in part to the averaging of rainfall in two regions with opposite characteristics. The correlation is positive for Indonesia west of 112°E and negative to the east. There is also an interdecadal trend of increasingly negative correlations from 1950–78 to 1979–97. The correlation changes from significantly positive (at 1%) to insignificant in western Indonesia and from insignificant to significantly negative in eastern Indonesia.

1. Introduction

During El Niño years, droughts tend to develop over the Maritime Continent (Ramage 1968), which consists of Malaysia, Indonesia, and the surrounding land and oceanic areas of the equatorial western Pacific between 10°S and 10°N (Fig. 1). These droughts can lead to strong environmental impacts, such as the large forest fires during the 1997/98 El Niño. However, several investigators (McBride and Nicholls 1983; Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Haylock and McBride 2001; Hendon 2003) have found that the strong negative correlation between Indonesian rainfall and tropical eastern Pacific SST occurs in northern summer and fall, which are the dry and transition seasons, respectively. During the northern winter monsoon, which is the wet season, the correlation tends to be a minimum. The correlation is low even though in northern winter the anomalous Walker circulation associated with ENSO events exhibits large-scale upper-level convergence over the Maritime Continent during warm events and divergence during cold events.

Because the identified influences of ENSO, including the anomalous Walker circulations and the SST anomaly (SSTA) away from the tropical eastern Pacific, are of

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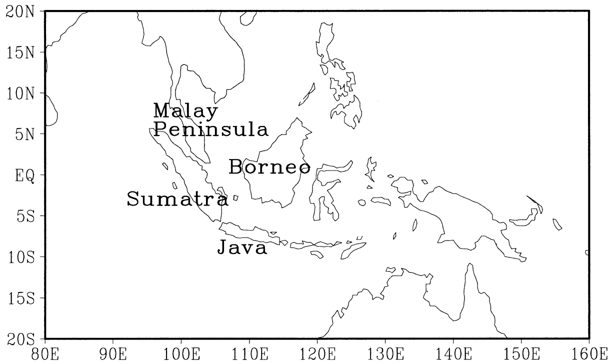

FIG. 1. Domain of study with geographic names of the western Maritime Continent.

very large scale, the study of the Maritime Continent rainfall–ENSO relationship is usually based on an area-averaged rainfall index. Typically this index is calculated over the entire area of study (e.g., Indonesia). Haylock and McBride (2001) calculated the spatial coherence of Indonesian rainfall anomalies among different stations and showed that over most of Indonesia the rainfall varies coherently on an interannual time scale during the transition season, but not during the wet season. They reasoned that the ''control'' of ENSO on the rainfall across the region is therefore effective only during northern fall and that the wet season rainfall in Indonesia is inherently unpredictable. Hendon (2003) further postulated that these coherence patterns result from the change of the feedback of ENSO on the Indonesian SST, which is due to the seasonal reversal of the prevailing winds. This change leads to the enhancement of the equatorial Pacific SST gradient and Walker circulation from the dry season to the transition season and a rapid reduction in the SST gradient and Walker circulation during the wet season.

On the other hand, the Maritime Continent spans an extensive spatial domain of complex terrain and includes several very large islands with high mountains separated by inner seas (Fig. 1). The domain is surrounded by several oceanic regions so that several important atmospheric and oceanic processes may influence different parts of this domain differently. This possibility is especially likely during northern winter when the region is affected by cold surges off the Asian continent from the north and Indian Ocean zonal wind anomalies from the west in addition to the events in the eastern equatorial Pacific (Lau and Chang 1987; McBride 1987). Therefore, certain parts of the domain may have localized relationships with ENSO during northern winter, even though the correlation between ENSO and the rainfall averaged over the entire region is low. The purpose of this study is to examine this possibility by analyzing data during 1979–2002, which is the period the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) rainfall data are available.

2. Data

Two overlapping sets of rainfall data are used. One is the CMAP data with global coverage produced by Xie and Arkin (1997), who derived the data by calibrating satellite cloud data with available rainfall reports. This dataset is available for 1979–2002. Another dataset is the 1950–97 Indonesian rainfall reports, which was made available by J. McBride of the Australian Bureau of Meteorology Research Centre. The reports more accurately represent the rainfall at each local station than the CMAP data but are available only within Indonesia. This dataset is used to cross-check some of the conclusions drawn from CMAP rainfall data and discuss the decadal variations over the southern Maritime Continent region. The wind data are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996) for 1979–2002, when CMAP rainfall is available.

The term northern winter defined here is the 3-month period from December of the preceding year to February of the current year (DJF). Unless specified otherwise, all figures shown are for the DJF season.

The SST data over the Niño-3 area (5°S–5°N, 150°–90°W) are used as an index to represent the ENSO events. The terms ''warm events'' and ''cold events'' refer to positive and negative SSTAs in the Niño-3 area. The results do not change significantly if the Niño-3.4 (5°S–5°N, 170°–120°W) SST is used as the ENSO index.

3. Results

a. Rainfall–Niño-3 correlations

The correlations between CMAP rainfall and Niño-3 SST during 1979–2002 are shown in Fig. 2. A generally negative correlation is present over most of the Maritime Continent. This negative area has a wider meridional extent to the east than to the west. A narrow belt of low correlation along the equator east of 130°E becomes wider toward the east. Farther east outside the domain (not shown), the pattern resembles a horizontal V that coincides with the familiar ''horseshoe'' pattern of SSTA associated with ENSO events [National Oceanic and Atmospheric Administration (NOAA) Climate Pre-

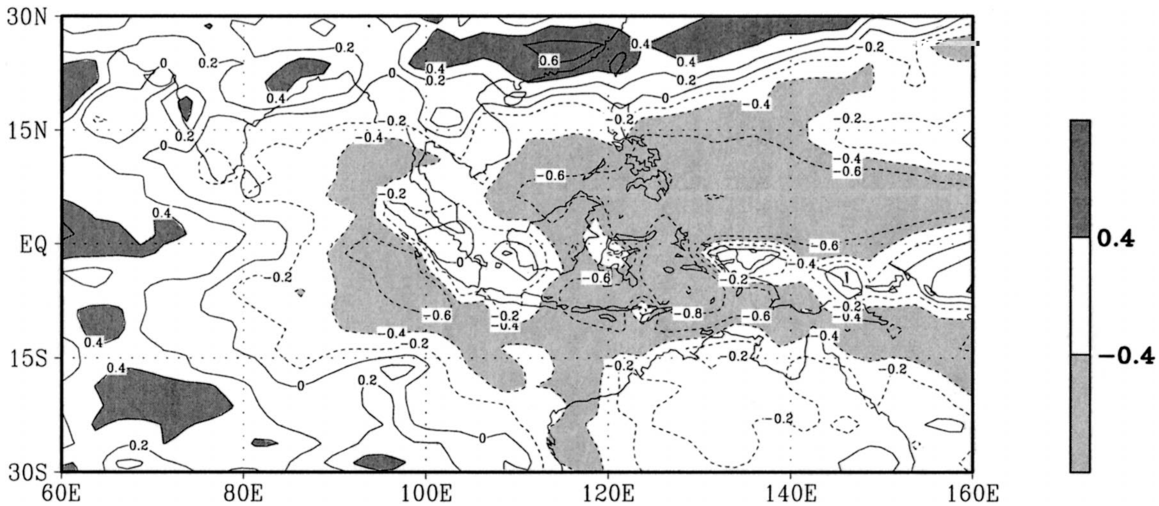

FIG. 2. Correlations of 1979–2002 CMAP rainfall with Niño-3 SST. Areas above the 5% significance level are shaded.

To analyze the possible causes of the spatial variations in Fig. 2, and particularly the appearance of a low positive correlation region in the vicinity of Sumatra and the Malay Peninsula, we define the following area-averaged rainfall indices to represent the rainfall variability in different regions (Fig. 3):

SMP: Sumatra and Malay Peninsula area;
SWO: southwest ocean area, which is the oceanic area immediately adjacent to the southwest coast of Sumatra; and
CMC: central Maritime Continent area.

A ‘‘SMP rainfall mode’’ may be delineated from the correlation between SMP and the CMAP rainfall (Fig. 4a), which shows that it is distinctly different from the ‘‘ENSO rainfall mode’’ in Fig. 2. On the other hand, the ‘‘SWO rainfall mode,’’ as described by the correlation between SWO and the CMAP rainfall (Fig. 4b), is very similar to the ENSO mode, with a conspicuous low correlation area in the Sumatra–Malay Peninsula area and the equatorial region east of 130°E. These different characteristics are confirmed by the correlations among the indices. The correlation between the SMP index and the SWO and CMC indices are 0.41 and 0.34, respectively, while the correlation between the SWO and CMC indices is significantly higher at 0.68.

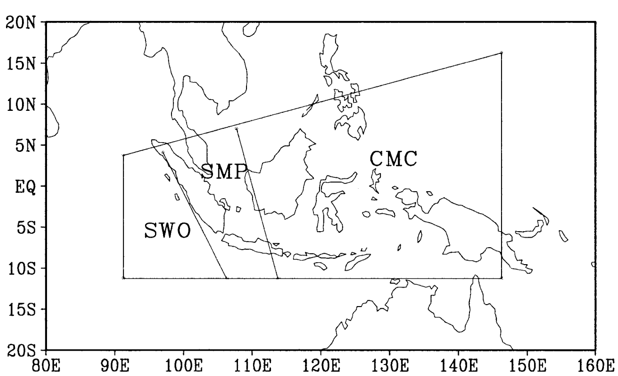

FIG. 3. Rainfall index regions.

The SMP mode in Fig. 4a has an east–west-spreading V shape with significant variances that extend into eastern Indian Ocean. As a result, the correlation between the area-averaged SMP index and the individual point rainfalls in the SWO region is higher (average 0.5) than that between the area-averaged SWO index and the individual point rainfalls in the SMP region (average 0.3). In fact, the correlations of SMP index with individual points inside the SMP region are low except for the northern Sumatra and the southern Malay Peninsula, which is a result of the often low coherence among rainfall at individual points within the region (Haylock and McBride 2001).

b. Composites of 850-hPa wind and vorticity according to Niño-3 SST and rainfall anomalies

The low correlation between the SMP rainfall index and Niño-3 SST suggests that the circulation patterns associated with the two indices may be quite different. To examine this difference, the composites of the 850-hPa wind from the NCEP–NCAR reanalysis are produced with respect to these two indices. Table 1 shows the cases for the Niño-3 warm and cold events and the SMP wet and dry events. The cases selected are those that have an anomaly of 0.75 or larger standard deviation within the CMAP data period of 1979–2002. A slightly positive correlation between the two indices is indicated by the two cold events in the dry SMP category and one warm event in the wet SMP category.

The anomalous Walker circulation associated with strong warm events (El Niño) is usually unfavorable for rainfall in the monsoon region. Therefore, the *cold* anomaly (*cold minus warm*) composite, rather than the *warm* anomaly composite, for Niño-3 SST is shown in Fig. 5

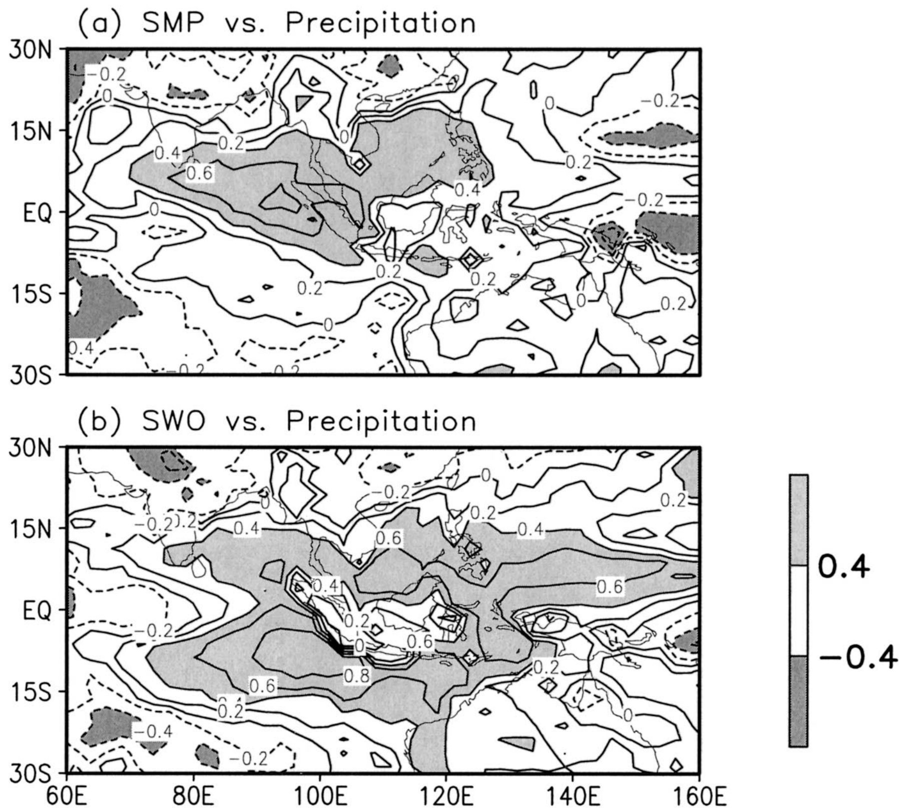

FIG. 4. Correlations of 1979–2002 CMAP rainfall with the (a) SMP rainfall index and (b) SWO rainfall index. Areas above the 5% significance level are shaded.

to facilitate the comparison with the *wet* anomaly (*wet minus dry*) composite. In Fig. 5a, the main aspect near the equator is the convergence of 850-hPa zonal wind around 150°E. This convergence is a manifestation of the anomalously strong rising motion related to the Walker cells over the Pacific and Indian Oceans that are typical of La Niña events. It is characterized by a belt of easterlies to the east of 150°E that can be traced from the eastern Pacific and a belt of westerlies to the west that encompasses about two-thirds of the Indian Ocean. The large-scale rising branch of the anomalous Walker circulation appears to favor convection in the eastern part of the Maritime Continent. In addition, an anomalous cyclonic circulation is centered near the Philippines and extends southwestward into the equatorial South China Sea. These patterns are consistent with the negative correlation between Niño-3 SST and rainfall over most of the Maritime Continent as shown in Fig. 2.

TABLE 1. DJF warm (bold) and cold (bold italic) cases for the Niño-3 SST index and wet and dry cases for the SMP rainfall index for 1979–2002. All cases have ≥ 0.75 std dev within the indicated periods.

Niño-3	
Cold	Warm
1985, 1989, 1999, 2000	**1983, 1987, 1992, 1998**
SMP	
Wet	Dry
1984, 1995, ***1999, 2000***	1979, 1980, 1982, 1997, **1998**

The SMP wet-minus-dry composite (Fig. 5b) has some similarities at the equator with the Niño-3 cold-anomaly composite in Fig. 5a. For example, the easterlies from the eastern Pacific and the westerlies from the Indian Ocean suggest two anomalous Walker cells with their ascent branches over the Maritime Continent. Although cyclonic wind anomalies are also indicated near southern Philippines and extend into the southern South China Sea, the anomalous vorticity patterns have considerable differences from the Niño-3 cold-minus-warm composite. The main vorticity anomaly in the vicinity of the Maritime Continent in Fig. 5a is a northward shift of the counterclockwise center from the Molucca area near the equator between 120° and 140°E during the warm anomaly to the southern Philippines during the cold anomaly. A secondary anomaly center in the southern South China Sea results from an in situ intensification of cyclonic vorticity. On the other hand, the SMP wet-minus-dry circulation in Fig. 5b is weaker, the vorticity anomalies in the southern Philippines–Molucca area are insignificant, and the in situ intensification

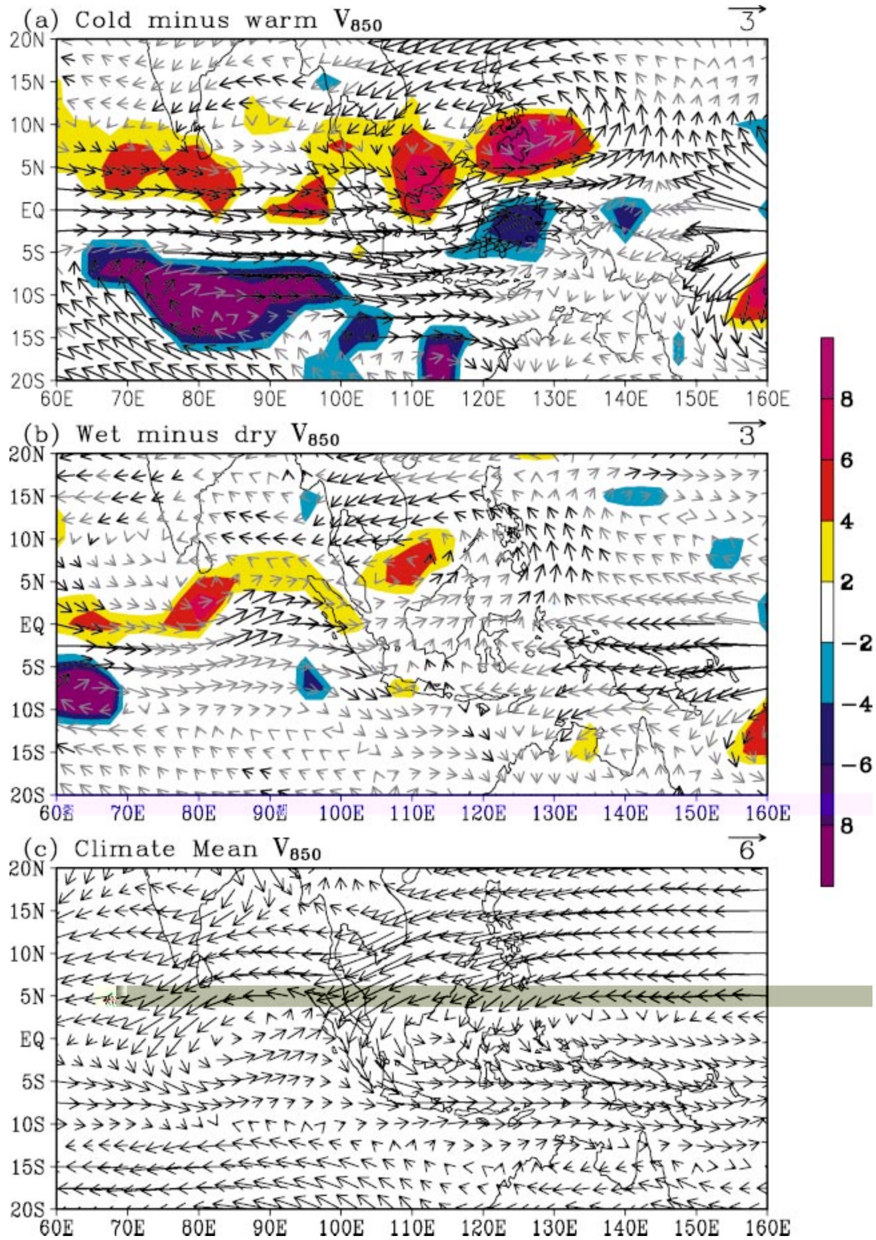

FIG. 5. (a) Composite of Niño-3 SST cold-minus-warm 850-hPa wind (m s^{-1}, heavy arrows indicate differences with at least a 95% confidence level in either the zonal or the meridional component) and vorticity (10^{-6} s^{-1}, only differences at 95% or higher confidence level are plotted) during 1979–2002. (b) As in (a) except for wet-minus-dry value in the SMP rainfall index. (c) Long-term seasonal (DJF) mean 850-hPa wind.

of the cyclonic vorticity in the southern South China Sea becomes the primary feature.

In the Indian Ocean, the Niño-3 cold anomaly (Fig. 5a) has significant cyclonic vorticity anomalies in both hemispheres straddling the equator with the strongest anomalies in the South Indian Ocean. Thus, this pattern corresponds to the strong equatorial westerly anomalies. An anomalous cyclonic vorticity center west of Sumatra is consistent with the negative correlation between the SWO rainfall and Niño-3 SST (Fig. 2). During the SMP wet anomaly, the significant cyclonic vorticity in central and eastern Indian Ocean occurs mostly north of the equator. It extends eastward to northern Sumatra and, together with the southern South China Sea cyclonic center, forms a pattern that is consistent with the V-shaped rainfall pattern in Fig. 4a.

The two composites have opposite anomaly signs in the southern equatorial belt between the equator and northern Australia. In the Niño-3 cold anomaly composite (Fig. 5a), the zonal wind direction is mostly west-

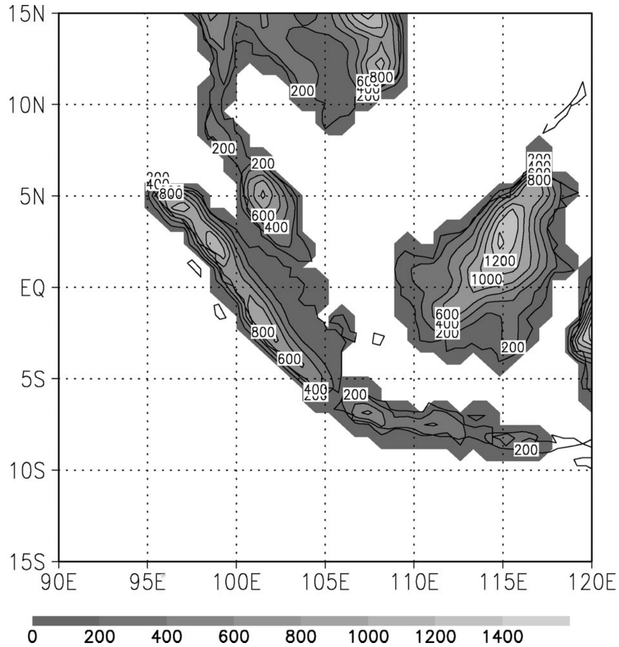

FIG. 6. Topography (m) in the area of study.

erly between 125° and 140°E while it is mostly easterly in the SMP wet anomaly composite (Fig. 5b). The mean 850-hPa wind field in this region during the northern winter monsoon (Fig. 5c) has prevailing westerly winds that are the result of the cross-equatorial flow from the Northern Hemisphere (Sumi and Murakami 1981; Johnson and Houze 1987). Thus, for cold events the anomalous circulation enhances the northern winter mean cross-equatorial flow, while for the SMP wet events it opposes the cross-equatorial flow. In the latter case, it is conceivable that the cross-equatorial monsoon wind is opposed upstream (north) of the equator, which will favor an anomalous 850-hPa convergence and more rainfall in the SMP region.

The 1979–2002 CMAP data are also used for the SWO wet anomaly composite of 850-hPa wind (not shown), which resembles closely that of the Niño-3 cold anomaly composite (Fig. 5a). The wet anomaly over the SWO area is apparently related to the anomalous westerlies from the equatorial Indian Ocean that are associated with the western anomalous Walker cell during cold Niño-3 events. Both the SWO and SMP wet anomaly composites contain an anomalous westerly wind over the equatorial Indian Ocean. In the SMP composite, the anomalous wind weakens near the longitudes of Sumatra–Malay Peninsula, which is consistent with the westward shift of the maximum cyclonic zone north of the equator over the South China Sea. In the SWO (and the Niño-3 cold event) composite, the anomalous wind is much stronger. It remains strong over the SMP area and does not attenuate until passing Borneo.

The high terrain along the west coast of the Sumatra peninsula (Fig. 6) may explain the differences in rainfall anomalies. When strong anomalous westerlies prevail over both the SWO and SMP regions, the moist air from the equatorial Indian Ocean produces excess rainfall on the windward side (SWO), but the influence on the lee side (SMP) is much reduced. The terrain has considerable fine structure. It may generate significant mesoscale features that are not resolvable by the large-scale reanalysis data. However, the effects on the large-scale circulations are significant enough to cause the rainfall difference between the two sides of the mountain ridge. As a result, SWO rainfall behaves as a component of the broader-scale ENSO circulations, while circulations associated with SMP rainfall variations are more limited spatially, which leads to a local low rainfall correlation zone with respect to ENSO.

Excess or deficit SMP rainfall can also lead to anomalous convergence or divergence in the region. It is not obvious whether the differences in the cross-equatorial flow and its associated large-scale divergence between the Niño-3 cold composite (Fig. 5a) and the SMP wet composite (Fig. 5b) noted before result from the SMP rainfall anomaly. Lau and Nath's (2000) general circulation model simulations predict a reduction of rainfall in the SMP area during La Niña events when regions to the east and west both have excess rainfall. Since their model's coarse resolution weakens the effect of the steep terrain, it appears that the anomalous cross-equatorial flow in the SMP wet composite (Fig. 5b) is an independent effect that makes the SMP rainfall less correlated with ENSO.

4. Discussion and conclusions

The above results demonstrate that rainfall over the Sumatra–Malay Peninsula region during the wet season (northern winter) has a weak positive correlation with Niño-3 SST. This is different from the ENSO–rainfall correlation for the rest of the Maritime Continent, which tends to be negative (except in the eastern equatorial area that appears to be associated with the horseshoe pattern of the ENSO effect in the western Pacific). Likewise, the CMAP rainfall data indicate that the oceanic region southwest of the Sumatra–Malay Peninsula also has a negative ENSO–rainfall correlation. Therefore, the interannual variation of the winter monsoon rainfall in the SMP region behaves differently from regions to the east and to the west.

The weak correlation between northern winter SMP rainfall and ENSO appears to be a result of the atmospheric anomalous pattern associated with ENSO events. This pattern includes a pair of anomalous Walker cells that are roughly symmetric with respect to the Maritime Continent, plus a synoptic-scale anomalous circulation center near the Philippines, and thus influences both the South China Sea and the Philippine Sea. Apparently, the influences of the eastern Walker cell and the Philippine Sea circulation diminish to the west so that the SMP region is less affected. On the other

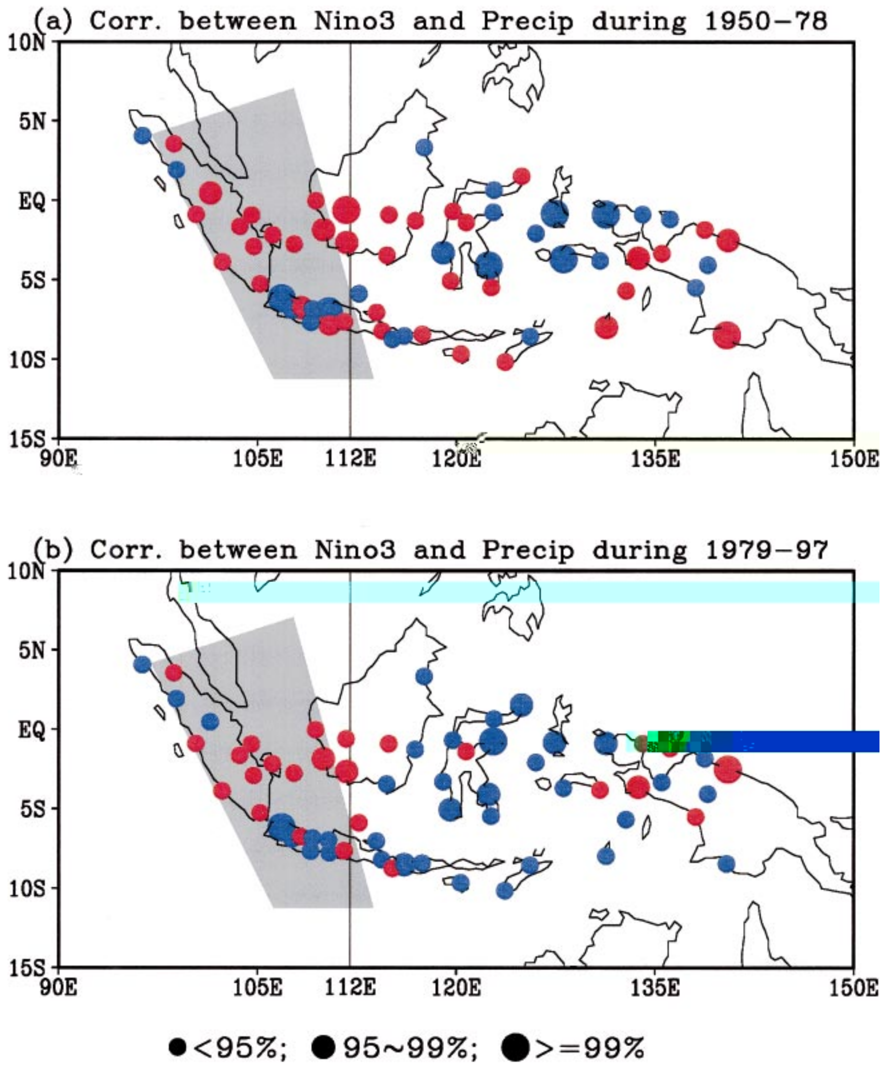

FIG. 7. Correlations of Indonesian station rainfall data with Niño-3 SST for (a) 1950–78 and (b) 1979–97. Positive (negative) correlations are indicated by red (blue) circles. The sizes of the circles indicate the significant levels, small: below 95%; medium: between 95% and 99%; and large: above 99%. The SMP region used in the analysis of CMAP rainfall is shaded.

hand, the influence of the western Walker cell over the Indian Ocean with an anomalous low-level equatorial zonal wind affects the oceanic region southwest of the island of Sumatra, but over the SMP region this effect is sheltered by the steep terrain along the west side of Sumatra. Rainfall in the SMP area is also affected by an anomalous cross-equatorial flow that is different from the typical circulation patterns associated with ENSO.

Our results show that during 1979–2002, the CMAP rainfall amounts over the central Maritime Continent, which includes a large part of Indonesia, are significantly correlated with Niño-3 SST (Fig. 2). This result contrasts with a number of previous investigations that found the Indonesian wet season rainfall to be uncorrelated with ENSO events (e.g., McBride and Nicholls 1983; Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Haylock and McBride 2001; Hendon 2003).

To investigate this difference, we cross-checked the rainfall—Niño-3 SST correlations using the same Indonesian station data as Haylock and McBride (2001) for 1950–78 and 1979–97 in Figs. 7a and 7b, respectively. Data outside of Indonesia are not available in these figures. In Fig. 7b, a mixture of positive (red) and negative (blue) correlations is seen in the SMP region (the shaded area), which indicates a weak correlation between Niño-3 SST and the area-averaged rainfall. Outside of the SMP region, more negative (blue) correlations are generally observed, which is consistent with the correlations from the CMAP data (Fig. 2). Another interesting point can be observed by comparing

TABLE 2. Correlation between Niño-3 SST and area-averaged Indonesian station rainfall for western Indonesia (west of 112°E), eastern Indonesia (east of 112°E), and all Indonesia. Values above the 1% significance are in bold. The significance of all other values is below the 7.5% level.

Winter (DJF)	1950–78	1979–97	1950–97
Western Indonesia	**0.49**	0.26	0.22
Eastern Indonesia	−0.25	**−0.62**	**−0.44**
All Indonesia	0.16	−0.30	−0.17

the correlations in the two periods. Outside of the SMP region, the number of stations with negative correlations (blue) significantly exceeds that of stations with positive correlations (red), especially during the later (1979–97) period. Thus, the Indonesia rainfall outside of the SMP region appears to become more correlated with Niño-3 SST after the late 1970s.

The subregional and interdecadal changes in Fig. 7 are more noticeable if Indonesia is separated into two subregions at 112°E. The correlations between Niño-3 SST and area-averaged Indonesian station rainfall for western, eastern, and all Indonesia are compared in Table 2 for 1950–78, 1979–97, and the entire period. The correlations are of opposite signs between western and eastern Indonesia, and the overall trend for the correlation is more negative in recent decades. From the earlier (1950–78) to the later (1979–97) periods, the correlation for western Indonesia weakens from significantly positive to low positive, while for eastern Indonesia it strengthens from low negative to significantly negative. The negative correlation for eastern Indonesia is also significant for the entire 48-yr period. By contrast, the correlation for all Indonesia remains insignificant regardless of the choice of data periods.

These results suggest that the low correlation between all-Indonesian rainfall during the wet monsoon season (boreal winter) and ENSO reported by previous studies may be in part due to the averaging of rainfall across the eastern and western regions that have opposite characteristics. The results also suggest an interdecadal change in which the correlation between Indonesian monsoon rainfall and ENSO becomes more negative beginning in the late 1970s. However, the wet season correlations remain lower than those of the dry (boreal summer) and transitional (boreal fall) seasons. This is especially so for January, which has consistently insignificant correlations for all regions and decadal periods.

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