On the Presence of Tropical Vortices over the Southeast Asian Sea–Maritime Continent Region

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ABSTRACT

Reanalysis and observation data from 1979 to 2010 are used to study the climatological behavior of regional vortices over the Southeast Asian sea–Maritime Continent region (SEAMC). After eliminating tropical cyclones from the International Best Tracks Archive for Climate Stewardship (IBTrACS), significant numbers of vortices remained over the region. The results also show that the vortices, rather than being relatively stationary near the Borneo coast in the winter, were consistently present over the SEAMC throughout the year, migrating from the area of the coast of Vietnam, the Philippines, and the Southeast Asian sea in summer to the island of Borneo region in winter. These vortices can produce significant amounts of rainfall in Vietnam, especially in central coastal regions during the postsummer monsoon (autumn) period.

1. Introduction

Early climate studies in the Southeast Asian region, published by Bruzon and Carton (1930), showed that the maximum monthly rainfall in Vietnam varies from north to south in accordance with the seasonal cycle. Their maps of monthly mean rainfall and monthly tropical cyclone activity during the period 1911–29 showed simultaneous occurrence of two climate elements in central Vietnam. However, the relationship between tropical cyclones and rainfall was not further investigated.

Since a low pressure system (or tropical vortex) in the Southeast Asian sea–Maritime Continent region (SEAMC; 10°S–25°N, 100°–120°E) can also produce heavy rainfall, we will include tropical cyclones (TCs) and less intense cyclones in the term Southeast Asian sea–Maritime Continent vortices (SMV). Nguyen and Nguyen (2004) summarized SMV activity over the Vietnam region (1960s–2000) and confirmed the migration of SMV from north (20°–23°N) to south (8°–10°N) associated with the seasonal change as noted in Bruzon and Carton (1930). In addition to the SMV's movement, there is a shift of maximum rainfall centers. SMVs mostly land in northern central Vietnam in June–July, whereas the central regions are affected in August–October. SMVs move southward and ceases in November–December.

However, when the tropical cyclone season endsnd in Vietnam, the aforementioned climatological rainfall centers keep moving southward. Studies such as those of Sadler and Harris (1970), Meehl (1987), and Chang et al. (2006) found the migration of rainfall centes from Indochina in October to the eastern coast of the Malay Peninsula and west of Borneo (2.5°N, 110°E) in November–December; these then migrated southward to the Java Sea and other Indonesian islands in January–February. The mechanism of this shift has been associated with the monsoon trough movement (Sadler and Harris 1970) or the movement of the northeasterly monsoon winds and their interaction with orography (Chang et al. 2006).

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In December 1978, the Winter Monsoon Experiment (WMONEX) was established with objectives to study both the global and regional aspects of the winter monsoon circulation over East Asia, the Maritime Continent, and Australia (Johnson and Chang 2007). WMONEX was the first and largest international effort to create a consistent dataset for specific research purpose. The WMONEX program made a significant contribution to the understanding of rain-producing cloud systems, diurnal convection, easterly waves, cold surges, and the Borneo vortices. The mechanism of winter rainfall in the Maritime Continent was partly explained by the presence of the Borneo vortices, formed by the equatorial easterly wave disturbances (Riehl 1948), the wind shear between two opposing flows (Sadler 1967), or the interaction between cold surges from East Asia and the monsoon trough (Cheang 1977). Chen et al. (2013) estimated that the Borneo vortices cause about 60% of total rainfall over North Borneo. The Borneo vortices were considered to be typical winter tropical vortices in the southern part the SEAMC.

Given the fact that there is the seasonal movement of rainfall centers along the SEAMC, our motivation in this study was to seek evidence of the existence of semipermanent vortices over the region. These vortices (i.e., SMV) migrate seasonally from the northern to southern SEAMC; and the Borneo vortices represent the southern limit of the SMV migration.

In this study, we investigated tropical vortex activity as it relates to the spatial and temporal extension of the Borneo vortices. In other words, we broadened the domain of study from the Borneo region to cover the full SEAMC region, and we investigated vortex activity throughout the year. Data and methods are introduced in section 2. Key findings are presented in section 3, and section 4 covers discussions and concluding remarks.

2. Data and methods

The Asian Precipitation–Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) dataset covers land areas. APHRODITE combined between 5000 and 12 000 stations from 1951 in the regions of the Himalayas, Southeast Asia, and the mountainous regions of the Middle East through the real-time World Meteorological Organization's Global Telecommunication System, data sharing from individual National Centre for Hydrometeorological Service, and the APHRODITE project's own collection (Yatagai et al. 2012). In this study, we extracted the monthly data from the 0.5° × 0.5° resolution daily dataset in the latest version of APHRODITE (V1101). Sixteen stations were used to illustrate the propagation of rainfall from north to south over the SEAMC (Fig. 1). The Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) was used over the ocean. Rain gauges, satellite data, and NCEP–NCAR reanalysis data were merged to produce the 2.5 × 2.5° gridded CMAP data globally. Only gridded points over the ocean in the core study domain (10°S–25°N, 100°–120°E; Fig. 1a) were selected. In addition, in situ daily rainfall observations at 60 stations in Vietnam (Nguyen et al. 2014) were also used to determine the vortex-induced rainfall.

Four different reanalyses are used here to detect the existence of tropical vortices: the Japanese 25-year Reanalysis (JRA-25; 2.5° × 2.5°; Onogi et al. 2007); the Japanese 55-year Reanalysis (JRA-55; 1.25° × 1.25°; Ebita 2011); the National Centers for Environmental Prediction–U.S. Department of Energy (NCEP–DOE, 2.5° × 2.5°) Reanalysis-2 (Kanamitsu et al. 2002); and the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; 1.5° × 1.5°; Dee et al. 2011).

The International Best Tracks Archive for Climate Stewardship (IBTrACS)/World Meteorological Organization tropical cyclone data (http://www.ncdc.noaa.gov/oa/ibtracs/index.php?name=wmo-data) was used to separate TCs from other vortices. The Nguyen and Walsh (2001) criteria was used to locate non-TC vortices that were less mature than TCs and not recognized by IBTrACS. This yielded four thresholds: 1) wind speed at least $5\,m\,s^{-1}$ at the 10-m level; 2) relative vorticity at least $1 \times 10^{-5}\,s^{-1}$ at 850 hPa; 3) total warm core temperature anomaly at 700, 500, and 300 hPa (T700 + T500 + T300) > 0°C; and 4) temperature anomaly at 300 hPa greater than that at 850 hPa. In general, the warm core and structure criteria were used to recognize the distinct difference between a tropical and high-latitude vortex. The domain used in this study is well inside the tropics, so thresholds 3 and 4 can be neglected. A vortex was considered to exist at a grid point if the relative vorticity and 10-m wind criteria were met using vorticity and 10-m wind averaged across the four closest neighboring grid points. Any vortex center less than 500 km from the coast was considered to be one that can produce rainfall over Vietnam. This 500-km-radius threshold is used widely both in research (Marks et al. 2002; Hattori et al. 2010; Dare 2013) and operational settings (e.g., NOAA, Hong Kong Observatory, and Vietnam Hydrometeorological Services) for the same objective. Particularly, the 500-km-radius criterion was used to determine the vortex-induced rainfall (VR) and IBTrACS tropical cyclone–induced rainfall (TR) days. Whenever a vortex associated with VR and TR appears over the SEAMC, stations within its 500-km radius werel be counted and assigned as affected stations. (In Fig. 4, the numbers of vortex-induced rainfall days at stations were interpolated to a regular 1° × 1° grid to improve readability.)

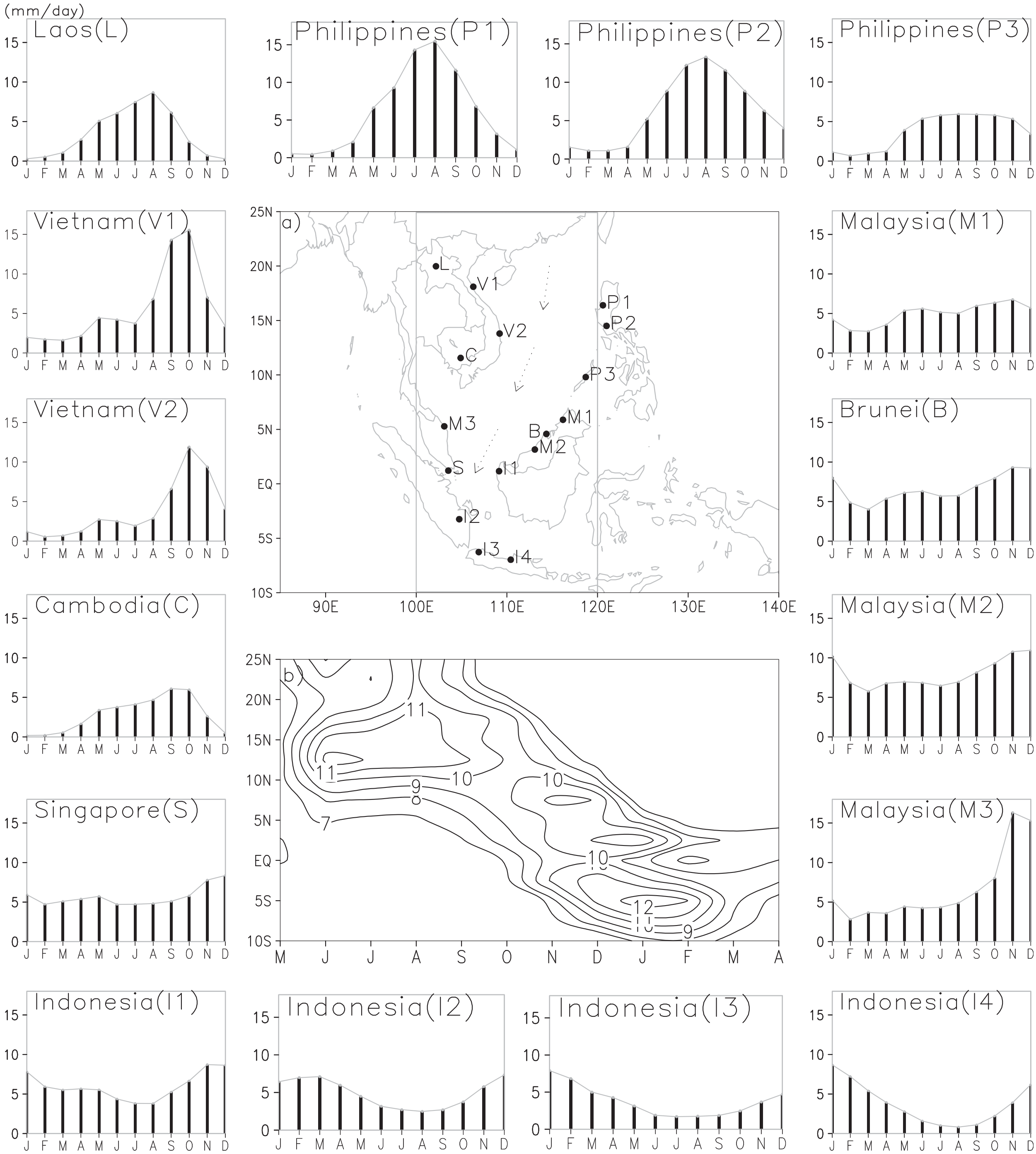

FIG. 1. (a) Map of ASEAN stations; surrounding the map is the monthly rainfall (mm day^{-1}) for these stations from APHRODITE. The temporal movement of rainfall over the region is shown by the dotted arrows. Stations used are in Laos [L (20.0°N, 102.2°E)], Vietnam [V1 (18.1°N, 106.3°E) and V2 (13.8°N, 109.2°E)], Cambodia [C (11.6°N, 104.9°E)], Singapore [S (1.2°N, 103.5°E)], the Philippines [P1 (16.4°N, 120.6°E), P2 (14.5°N, 121°E), and P3 (9.8°N, 118.7°E)], Malaysia [M1 (5.9°N, 116.2°E), M2 (3.2°N, 113.1°E), and M3 (5.3°N, 103.1°E)], Brunei [B (4.6°N, 114.4°E)], and Indonesia [I1 (1.2°N, 109.1°E), I2 (3.3°S, 104.8°E), I3 (6.3°S, 106.9°E), and I4 (7.0°S, 110.4°E)]. The core domain of study is 10°S–25°N, 100°–120°E. (b) Hovmöller diagram of monthly CMAP plotted.

TABLE 1. Temporal and spatial features of winter tropical disturbances over the southern South China Sea in or close to the framework of WMONEX.

Reference	Focus time	Focus domain	Key words
Ramage (1968)	Jan 1963 and 1964	20°S–30°N, 90°–160°E	Latent heat released.
Cheang (1977)	Dec 1973	20°S–30°N, 90°–140°E	Borneo vortex genesis.
Chang et al. (1979)	Dec 1974	5°S–25°N, 100°–125°E	Cold surges and vortices.
Houze et al. (1981)	Dec 1978	Borneo	Structure and time variation of cloud and precipitation.
Churchill and Houze (1984)	Dec 1978	0°–20°N, 100°–120°E	Structure and development of cloud clusters.
Johnson and Houze (1987)	Dec 1978–Mar 1979	20°S–20°N, 100°–120°E	Convective clouds.
Chang et al. (2003)	Dec 2001	10°S–12.5°N, 100°–120°E	Typhoon Vamei.
Chang et al. (2005)	Dec 1980–Feb 2001	10°S–15°N, 90°–120°E	Borneo vortex, Madden–Julian oscillation, and cold surges.
Tangang et al. (2008)	Dec 2006–Jan 2007	10°S–10°N, 90°–130°E	Borneo vortex, Madden–Julian oscillation, and Indian Ocean dipole.
Koseki et al. (2014)	Dec 1981–2008	10°S–20°N, 90°–130°E	Borneo vortex mechanism, meso-α cyclone, and meso-β rainfall.

The 32-yr period from 1979 to 2010 for all datasets (observations, APHRODITE, CMAP, reanalyses, and typhoon tracks) was selected in this study.

3. Initial results

Some of the earlier studies of the Borneo vortices are listed in Table 1. Only a few studies have looked at the whole SEAMC domain; and the majority (not shown in Table 1) were only conducted for limited regions. The limited nature of these studies is even clearer if we consider the time periods. Recall that WMONEX occurred over four months, December 1978–March 1979, but most data from radar, ships, and aircraft were taken during the single month of December 1978.

Figure 1 illustrates the rainfall climatology for the stations in 8 out of 10 countries of the Association of Southeast Asian Nations (ASEAN). Both continental and ocean rainfall show a migration of rainfall over this region, from the northern Southeast Asian sea in September–October down to the southern Maritime Continent in January–February. This feature is consistent with previous studies (e.g., Sadler and Harris 1970; Meehl 1987; Chang et al. 2006).

Figure 2 shows the total number of vortex occurrences for all months during the 32 years (1979–2010). Around

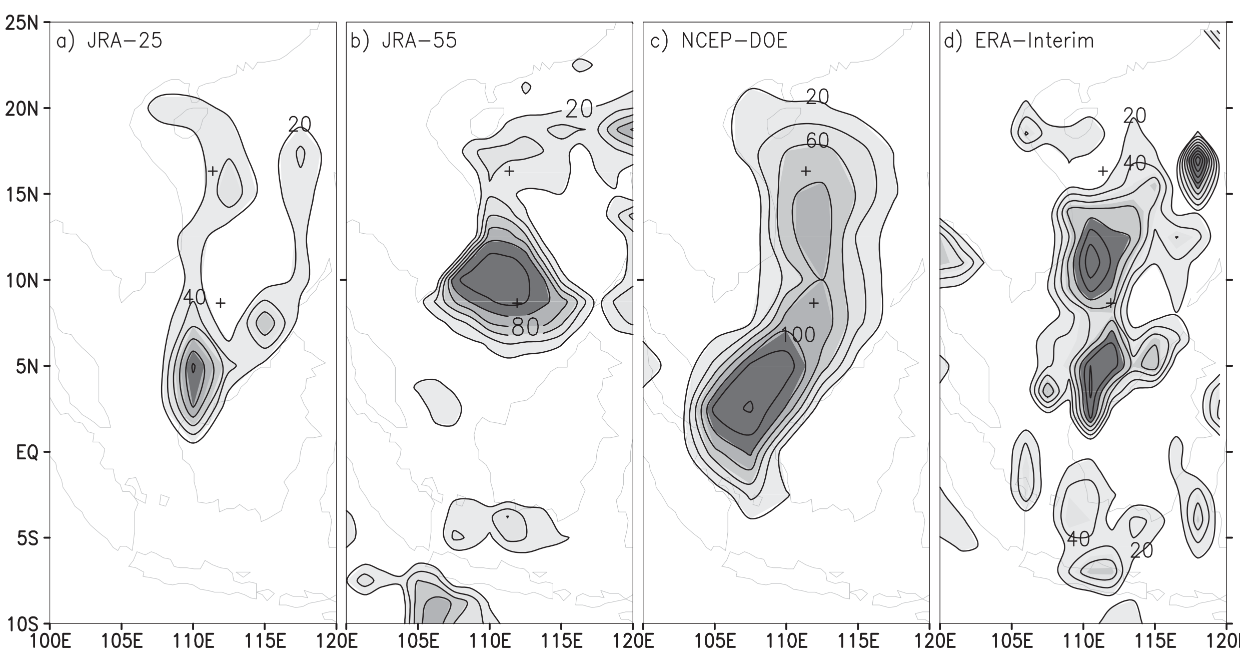

FIG. 2. Number of monthly vortices from reanalysis datasets over each ocean grid point over SEAMC during 1979–2010. The contour interval is 20: (a) JRA-25 (2.5° × 2.5°), (b) JRA-55 (1.25° × 1.25°), (c) NCEP–DOE Reanalysis-2 (2.5° × 2.5°), and (d) ERA-Interim (1.5° × 1.5°).

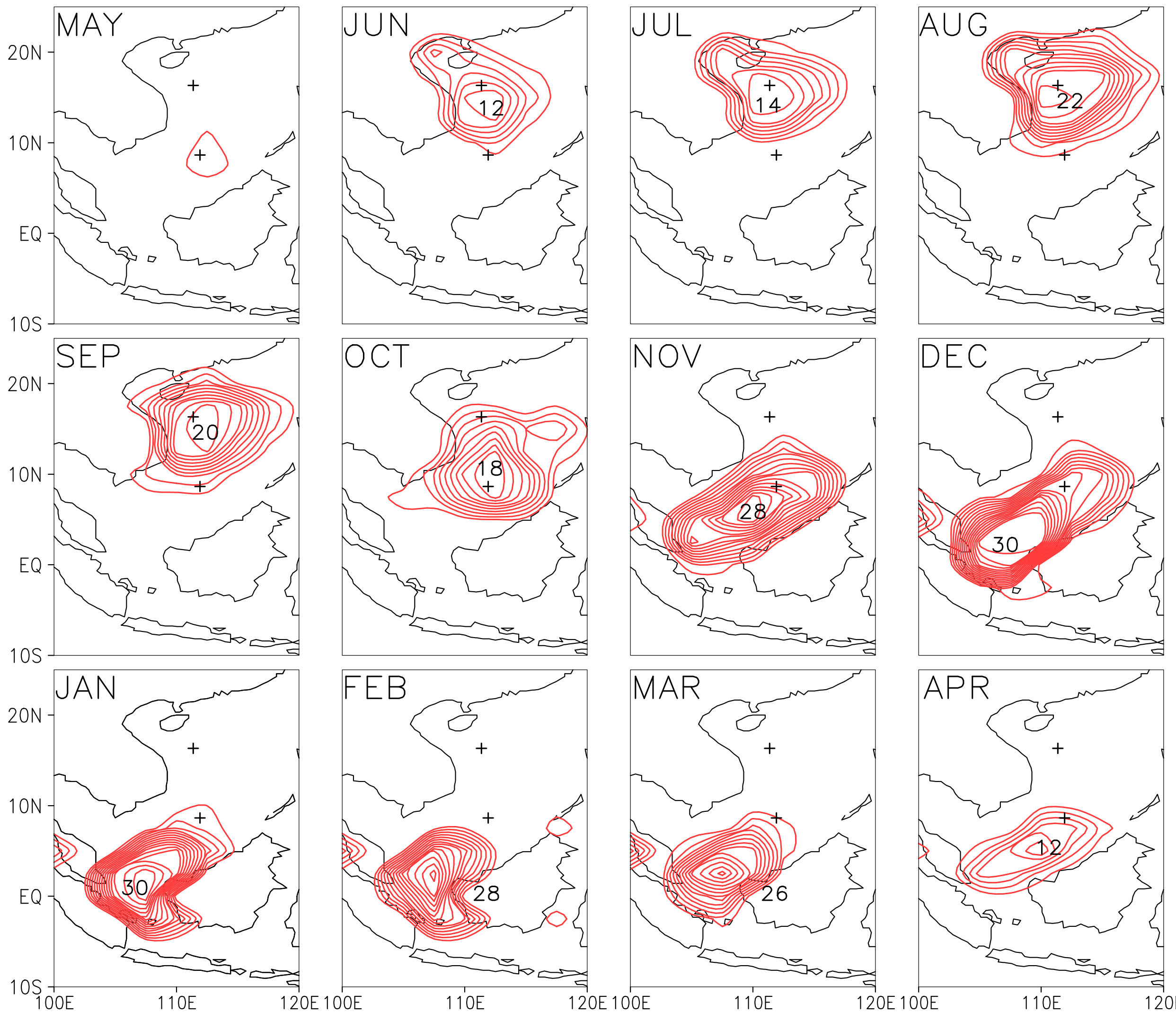

FIG. 3. Monthly occurrence of vortices over the sea in SEAMC in the NCEP–DOE Reanalysis-2 (1979–2010). Contours indicate the number of vortices in each month with an interval of 2; the figures plotted show the maximum number. The plus (+) signs indicate HoangSa (north) and TruongSa (south) island stations.

the island of Borneo, there is a high concentration of vortex occurrences, as many studies have shown previously. The interesting finding here is that the vortex can appear throughout the SEAMC region, not only in the Borneo–Singapore region.

We developed a seasonal evolution of the SMV that depicts monthly vortex counts in individual reanalyses during 1979–2010. The summer-to-winter movement of SMVs in the NCEP–DOE Reanalysis-2 is most consistent with the regional rainfall distributions prepared by Sadler and Harris (1970), Meehl (1987), and Chang et al. (2006); this is shown in Fig. 3 (figures from different reanalyses are not shown). Contours show the number of vortex occurrence in each month. The average SMV location migrates north to south across the region, passing two stations named HoangSa and TruongSa (Fig. 3), from summer to winter. The averaged probability of the existence of vortices in the region varies by season, increasing from a minimum of about 20% in April–May to 50% in June–August, 70% in September–November, and 85% in December–March. In the summer months, June–August, the SMV's location is farthest north, about 21°N, extending zonally from the Gulf of Tokin to the TruongSa station, in the northern central Southeast Asian sea. Three months later, its mean position is close to the HoangSa station, on the central coast of Vietnam; during this time SMVs can form as far south as the island of Borneo. In winter, the SMV mean position is around Borneo.

SMVs, as defined earlier, include TCs as well as less intense cyclones. In fact, the criteria to detect vortices do

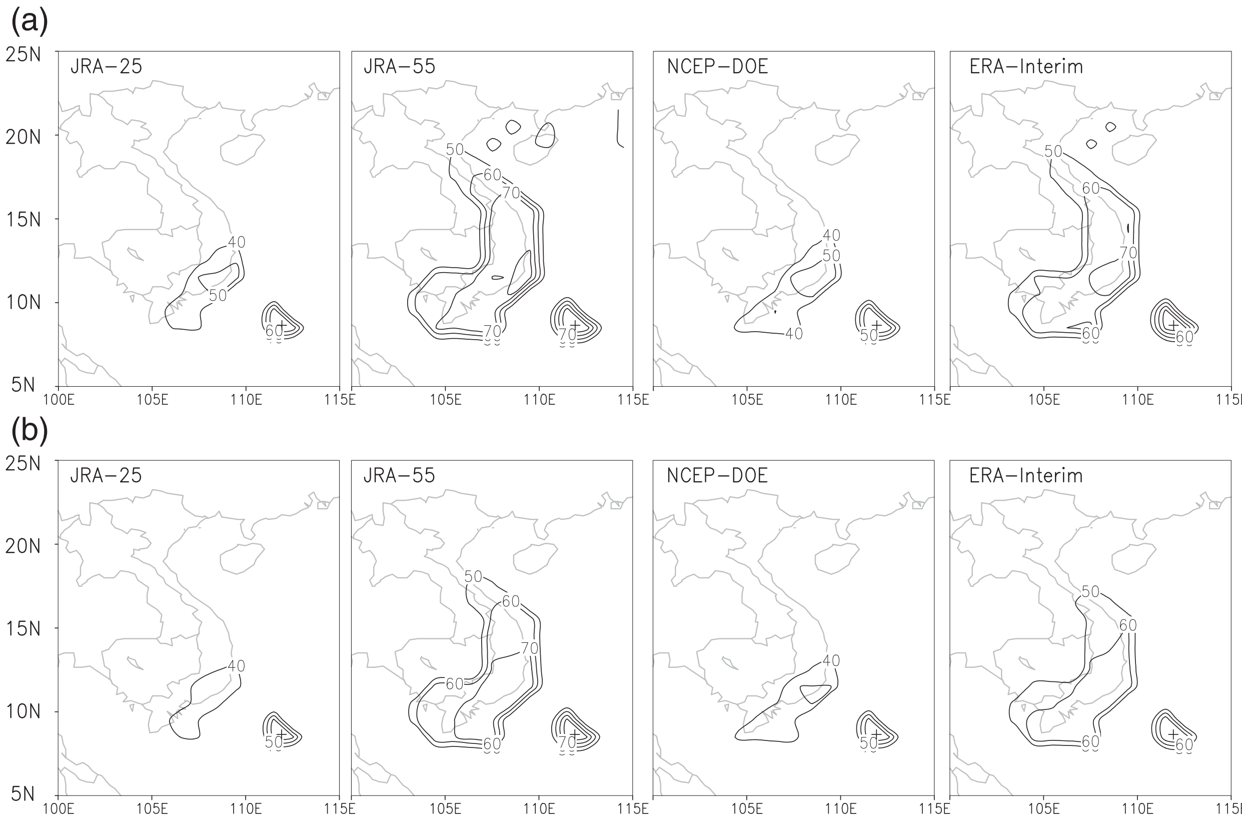

FIG. 4. (a) Vortex-induced rain days (VR), as a percentage of the total number of days (11 680) in the 32-yr record (1979–2010). Contour interval is 10%. Only regions that have VR ≥ 40% are displayed. The plus (+) sign indicates TruongSa island station. (b) As in (a), but with tropical cyclones eliminated using IBTrACS.

not have any indication of the location of formation and movement. In other words, vortices in Figs. 2 and 3 consist of not only those forming and moving inside the SEAMC region, but also TCs coming into the region from the northwestern Pacific. To confirm the existence of semipermanent vortices, we removed all TCs identified in the IBTrACS database from the set of daily vortex occurrences and reassessed the remaining vortices, as discussed in the following section.

4. Southeast Asian sea–Maritime Continent vortex

Figure 4 shows the vortex-induced rain days at each station. The four different reanalysis datasets display the highest and most consistent frequency of rain days around the southern coast of central Vietnam. The number of VR days varies from 50% in JRA-25 (equivalent to 5840 days of the total 11 680 days in 1979–2010) to 80% in JRA-55 (Fig. 4a). A sensitivity test was carried out to determine the dependence of the number of VR days on the spatial resolution of the reanalysis datasets. The JRA-55 and ERA-Interim reanalyses were resampled to 2.5° × 2.5° latitude–longitude resolution and the VR days recalculated. The new VR days patterns in JRA-55 and ERA-Interim were almost the same as in NCEP–DOE Reanalysis-2 and JRA-25: the number of VR days maximizes on the southern coast, and is about 50%–55% of total days in 1979–2010. It therefore appears that the presence of permanent vortices is not sensitive to horizontal resolution.

Moreover, the very high number of VR days on the southern coast of Vietnam is not fully linked to the larger number of TCs in the area. The maximum frequency of 50% (e.g., in JRA-25) means one of every two days (on average) is affected by vortex activity in that region. The IBTrACS tropical cyclone track data for 1979–2010 show that there were 334 TCs observed over the domain 3°–25°N, 100°–120°E. On average, each TC over this domain lasted 3–5 days, and therefore the maximum total IBTrACS tropical cyclone–induced rainfall days over the region was about 1000–2300 total days during 1979–2010, equivalent to only 10%–20% of identified VR days in total. If TR days are extracted from Fig. 4a, a significant remainder of VR days is left. Figure 4b depicts the VR days after the TR days were removed from each reanalysis dataset. There are obvious reductions of up to approximately 20%, but the patterns remain the same in all cases.

The rainfall associated with VR days (Fig. 4b) demonstrated the presence of semipermanent vortices on the south coast of Vietnam and the Philippines. This summer component and the winter component (Borneo vortices) illustrate a complete annual cycle of semipermanent vortices over the SEAMC region.

5. Discussion and concluding remarks

The Southeast Asian sea–Maritime Continent vortex has been called an equatorial vortex–disturbance (Cheang 1977; Houze et al. 1981), Borneo vortex (Chang et al. 2005), tropical depression–type disturbance (Yokoi and Matsumoto 2008), and cold surge vortex (Chen et al. 2012). The analysis presented here shows the existence of vortices through the whole seasonal cycle and over the full latitude range of the SEAMC region. It suggests that this phenomenon could be more accurately known as the SMV.

The SMV first appears in coastal northern Vietnam and the western Philippines in summer, moves southward during autumn, reaches Singapore and Borneo in winter, and stays around the Borneo region into spring until a new yearly cycle begins again in summer. The frequency of the SMV occurrence is highest in winter and then decreases gradually in spring, summer, and autumn. This annual variation aligns well with the picture of the seasonal onset of rainfall over the region (Fig. 1).

The SMV can develop and be organized into a tropical cyclone. In the last 62 years (1952–2013), at least one TC formed each year in the Southeast Asian sea region (according to the IBTrACS dataset), except in 1969 and 2006. These two years show no TCs formed in the region. In contrast, 5 years (1965, 1983, 1997, 2002, and 2009) experienced more than five TCs in the region. Although cyclone genesis associated with the SMV is beyond the scope of this study, we expect that studying the extreme high and low TC years may give more insights on the thermodynamic aspects of SMVs.

In addition, since this study has not investigated the change of track and intensity of SMVs, relationships between large-scale forcing such as ENSO and the MJO in last decades and SMV characteristics could be interesting future works.

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