Development and Formation Mechanism of the Southeast Asian Winter Heavy Rainfall Events around the South China Sea. Part I: Formation and Propagation of Cold Surge Vortex*

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ABSTRACT

Examination of the development of cold season heavy rainfall/flood (HRF) events around the South China Sea (SCS) from their parent cold surge vortices (CSVs) shows three new development processes. First, the formation mechanism of the parent CSV of an HRF event [CSV(HRF)] has a preference as to geographic location, flow type of the cold surge inside the SCS, and time of day. The surface trough east of the Philippines, Taiwan, and southern Japan island chain in late fall and the near-equator trough across Borneo in winter facilitate the CSV(HRF) formation in two regions—the vicinity of the Philippines and Borneo. The formation of the Philippine (Borneo) CSV(HRF) occurs at 0600 UTC (0000 UTC) with involvement from the Philippine Sea (PHS)-type (SCS type) of cold surge flow. Second, the flow type of the cold surge determines the CSV(HRF) propagation across the South China Sea. The PHS-type (SCS type) facilitates (hinders) the CSV(HRF) westward propagation. This occurs because the easterly (northerly) flow is greater than (less than) the northerly (easterly) flow at the maximum isotach location of the cold surge flow associated with CSV(HRF) and is centered east of the demarcation line for propagation. This flow-type contrast is substantiated by the vorticity budget analysis for CSV(HRF). The positive 925-hPa vorticity tendency is located west of (coincident with) the 925-hPa vorticity center for the PHS-type (SCS type) of cold surge. Third, the CSV(HRF) development into a HRF event is achieved through multiple interactions of former vortices with sequential cold surges across the South China Sea. The first two CSV(HRF) development processes are reported herein; the last process is presented in Part II.

1. Introduction

The major cold season weather/climate system in Southeast Asia, particularly the heavy rainfall flood (HRF) event, is developed by the midlatitude–tropic

interaction through the East Asian cold surge. The impact of this interaction is reflected by the seasonal variation of the rainfall climatology over the countries around both sides of the South China Sea, indicated by World Meteorological Organization (WMO) surface stations (Fig. 1a, red dots). Rainfall along these two coastal lines exhibits a southward seasonal migration from the north (15°–20°N) in late fall to south of the equator in winter. This is shown by rainfall centers along each coastal line in the rainfall latitude–time (y – t) diagram: 1) central Vietnam, peninsular Malaysia, and Sumatra–Java along the west coast of the South China Sea (SCS) (Fig. 1b) and 2) the northern Philippines,

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FIG. 1. (a) WMO surface stations (dark blue and red dots) in Southeast Asia, but only rainfall measurements of stations marked with red dots are used to make the rainfall y - t diagrams along both sides of the South China Sea. The seasonal evolution of rainfall along (b) the east coast of Vietnam, peninsular Malaysia, and Sumatra-Java, and (c) the east coast of the Philippines and the west coast of Borneo.

Mindanao, and northwestern Borneo west of the SCS (Fig. 1c). These phenomena were observed and analyzed by our recent studies; the rainfall centers in central Vietnam (Chen et al. 2012a) and Malaysia (Chen et al. 2013a,b) are primarily produced by HRF events identified by the Dartmouth Flood Observatory (DFO; DFO 2013; <http://floodobservatory.colorado.edu/>) for the last few decades. Shown in Fig. 2 are 181 HRF events in Southeast Asia during the 1979–2012 period: 83 events occurred in Indochina and Borneo during 1979–2012, and 98 events occurred in the Philippines and Sumatra-Java during 1992–2012.

Observed by Cheang (1977), the winter rainfall in tropical Southeast Asia is primarily produced by the intensified equator vortex in the presence of the northeast Asian cold surge flow. This observation was confirmed by the cold surge vortex (CSV; formed by the interaction between the easterly wave and the cold surge flow) in tropical Southeast Asia by Chen (2002) in search of the forcing mechanism of the trans-Pacific winter

shortwave train. After an examination of the environment conducive to the occurrence of heavy rainfall vortices in central Vietnam, Yokoi and Matsumoto (2008) claimed the coexistence of a tropical depression-like vortex and a cold surge flow is a required condition. To obtain a more in-depth understanding of the formation mechanism of the HRF cyclone and/or noncyclone event (cyclone/event) in central Vietnam, Chen et al. (2012a) recently explored the synoptic development of this mechanism from the perspective of midlatitude-tropic interactions through the cold surge flow involved with the formation and development of the parent CSV. Four identified synoptic features pertaining to the present study are listed:

- 1) The parent CSV of an HRF cyclone/event, herein called CSV(HRF), is formed by the interactions between an easterly wave and the East Asian cold surge flow in the vicinity of the Philippines or between the East Asian cold surge flow and Borneo orography.

- 2) Basic characteristics (including speed, size, and rainfall) of CSVs, which evolve into HRF cyclones/events, are well distinguishable one day after their formation against the nondeveloping CSV.
- 3) Occurrences of the central Vietnam HRF events synchronize with those of the northwestern Pacific explosive cyclones.
- 4) Indicated by the 850-hPa zonal wind, maximum speed for the HRF cyclone/event easterlies, tropical trade easterlies from the North Pacific anticyclone, and westerlies from the northwestern Pacific explosive cyclone occur simultaneously.

Although synoptic features about the formation of CSV(HRF) and their development into HRF cyclones/events have been documented by our previous studies, the formation locations, propagation properties (inferred from their trajectories), and the development process of CSV(HRF) into HRF cyclones/events (shown in Fig. 2) lead to the following issues regarding this development mechanism:

- 1) The CSV(HRF) formation only occurs in two regions—the vicinity of the Philippines and Borneo. The interaction of cold surge flow with easterly waves or orography should not be restricted only to these two regions. So, what causes the geographic preference of CSV(HRF) formation? Some special environmental conditions restrict the CSV(HRF) formation in these two regions.
- 2) Observed by Chen et al. (2013a), the peninsular Malaysia HRF events are developed by the westward-propagating parent CSV(HRF) from both the vicinity of the Philippines and Borneo. However, the Borneo HRF events evolve from their in situ parent CSV(HRF) that stagnate in Borneo. The westward propagation of CSV(HRF) is determined by the cold surge flow type, as classified by Compo et al. (1999)—the SCS and the Philippine Sea (PHS) types. We will test whether this hypothesized mechanism of the CSV(HRF) propagation property is applied to all CSV(HRF) around the South China Sea.
- 3) The basic characteristics (size, speed, and rainfall) of HRF cyclones/events are much larger/stronger than their parent CSV(HRF). So far, the development mechanism of these CSV(HRF) into HRF cyclones/events has not been explored or understood. Both formations of CSV(HRF) and HRF cyclone/event are involved with interactions of CSV(HRF) with different cold surge flows. The development time and traveling distance between formation locations of CSV(HRF) and HRF events may be 2–10 days between the equator and 25°N. Therefore, we may

question if some HRF cyclones/events develop from their parent CSV(HRF) by interacting with more or less than two different cold surge flows.

The large contribution of HRF events to the rainfall centers west of the South China Sea (Fig. 1) suggests that other rainfall centers around the South China Sea are also primarily formed by HRF events. Thus, an effort is made in this study to explore the three aforementioned issues related to the development mechanism of CSV(HRF) into HRF events around the South China Sea. The results will be presented in two parts; the first two issues are addressed here (the present paper) and the third issue is reported in Chen et al. (2015, hereafter Part II). The first part of this study is structured and reported in the following manner. Data used in the study are described in section 2. Elements of the large-scale monsoon circulation conducive to the CSV(HRF) formation are portrayed in section 3. Synoptic conditions of CSV(HRF) formation and development into a HRF cyclone/event in rainfall centers along both coasts of the South China Sea are shown in section 4. In this section, confirmation of the CSV(HRF) formation mechanisms is made with the synoptic analysis. Statistics for the synoptic features crucial to the CSV(HRF) formation mechanism are presented in section 5. The propagation properties of CSV(HRF) and the mechanism regulating these properties substantiated by the vorticity budget analysis are illustrated in section 6. A summary of the results presented in this study, concluding remarks, and suggestions for future studies are offered in section 7.

2. Data and identification of a CSV(HRF), HRF event, northwestern Pacific explosive cyclone, and shallow surface trough

a. Data

Datasets used for the present study are updated and expanded from those used in our previous analyses for the cold-season rainfall in Vietnam (Chen et al. 2012a) and Malaysia (Chen et al. 2013a, their Table 1) in two ways: 1) the length of the data coverage period and 2) the domain. First, the data period of 1979–2008 for the cold season rainfall studies of Vietnam and Malaysia is expanded to include 2012, and second, the data domain of Chen et al. (2012a, 2013a) is retained and expanded as described below.

1) RETENTION

- Regional rainfall and satellite data from the Asian Precipitation–Highly-Resolved Observational Data

FIG. 2. Formation locations of propagating CSV(HRF) (solid red or blue dots), nonpropagating CSV(HRF) (open red or blue circles), HRF event (crosses), CSV(HRF) trajectory (thin red line), and precipitation (blue) superimposed on the 925-hPa streamline chart, for (a) October–November, (b), (c) November–December, (d) October–February, and (e) December–February. CSV(HRF) reaching (stagnated) the west (east) side of the South China Sea are shown on the left (right). Red thick dashed lines and purple thick dashed lines mark the near-equator trough and the island-chain trough, respectively. Countries affected by HRF events and numbers of HRF events in these countries are shown in the upper left corner of each panel. Formation location of CSV(HRF) and occurrence location of HRF event are marked by dots and crosses in red or blue for different regions indicated by abbreviations provided in the bottom right corner. Location of Borneo CSV(HRF) related to Borneo and Java HRF HRFs are marked by red and blue open circles in (e).

Integration Toward Evaluation of Water Resources (APHRODITE, v1204R1) rainfall over the Asian land area and the regional blackbody temperature T_{BB} measured by the Geostationary Meteorological Satellite (GMS) series, *GOES-9*, and Multifunction Transport Satellite (MTSAT) series;

- global rainfall and rainfall proxy from TRMM, GPI, GPCP, and MSU;
- global reanalyses/initial analyses from NCEP GFS, ERA-Interim, and GEOS-5, and NOAA OISSTv2 for global sea surface temperature;
- daily surface maps issued by NCEP Service Records Retention System (SRRS), JMA, and the Thai Meteorological Department (TMD);
- DFO HRF events over Vietnam and Malaysia; and
- The northwestern Pacific explosive cyclones identified with the Sanders–Gyakum 24 hPa day^{−1} criterion and its synchronous formation with the occurrence of HRF events of central Vietnam and Malaysia.

2) EXPANSION

- The WMO surface observations in Vietnam, Malaysia, the Philippines, and Indonesia around the South China Sea are analyzed;
- the Australian Bureau of Meteorology (BoM) daily surface maps are also utilized to verify the synoptic development of CSV(HRF) and HRF events over southeastern Sumatra and Java depicted by daily maps of other operational agencies;
- the DFO HRF events include southeastern Sumatra, Java, and the Philippines, and all HRF events around the South China Sea analyzed are verified with the International Emerging Disaster Database (EM-DAT 2013); and
- the analysis of HRF events covers seven rainfall centers around the South China Sea, and the identified northwestern Pacific explosive cyclones related to the HRF events of the Philippines and Indonesia are included.

A summary of the information (source, resolution, domain, and period) of both the retained and expanded datasets is presented in Table 1.

b. Identification of the cold surge vortex, cold surge type, and relevant synoptic elements

1) HRF COLD SURGE VORTEX

About 60% of the cold season rainfall over central Vietnam (Chen et al. 2012a) and Malaysia (including peninsular Malaysia and Borneo; Chen et al. 2013a,b) is produced by HRF cyclones/events. These cyclones/events develop from the Philippine and Borneo CSV(HRF).

The procedure that identifies these CSV(HRF) in the present study is updated from our previous studies with new findings from the CSV formation mechanisms presented in sections 4 and 5:

- Step 1: As shown in the 925-hPa streamline chart (Fig. 2), the “Philippine CSV” is a closed vortex formed in the vicinity of the Philippines by the interactions of an easterly wave with the PHS-type cold surge flow and the island-chain trough (defined in section 3). Emerging from the 925-hPa streamline chart, the “Borneo CSV” is a closed vortex over northwestern Borneo formed by the interaction of the SCS-type cold surge flow with the cyclonic shear flow around the near-equator trough and Borneo orography.
- Step 2: The identified CSVs are verified against available operational surface analyses—the NCEP 6-h SRRS charts, and surface analysis charts for JMA, TMD, and BoM.
- Step 3: The preferred formation time of the Philippine CSV(HRF) is 0600 UTC (between 0300 and 0900 UTC), whereas that for the Borneo CSV(HRF) is 0000 UTC (between 2300 and 2400 UTC).
- Step 4: A backtracking approach is adopted to trace all HRF cyclones/events identified by the DFO, verified by EM-DAT, from their occurrence locations to the formation locations of their parent CSVs.

2) COLD SURGE TYPE

To explore its impact on the local weather system, cold surge is often defined with surface pressure increase (Δp_s), surface temperature drop (ΔT_s), and the passage of surface wind surge measured at a selected location. For the current study, the major concern is the flow type of cold surge related to two major issues: 1) the CSV formation and 2) the CSV(HRF) propagation property.

- Issue 1: The flow type of cold surge related to the CSV formation.

Compo et al. (1999) traced the preferred paths and classified the East Asian cold surges into the PHS and the SCS types. Based on spectral analyses of surface pressure and 850-hPa zonal wind, they selected two base points to depict the cold surge flow pattern with a regression approach: 20°N, 140°E as the PHS base point and 15°N, 115°E as the SCS base point. Compo’s et al.’s approach is adopted by a modification. (A brief description is given here, but further detail is provided in the first part of the supplemental material).

(i) The PHS type of cold surge:

The northeast Asian cold surge of the PHS type directs east-southeast from northeastern China into

TABLE 1. Detailed information of datasets used in this study.

Data	Source	Spatial resolution	Spatial domain	Temporal resolution	Data period	Source information
Rainfall Surface observation	WMO surface stations:					http://www.ncdc.noaa.gov/oa/climate/climatedata.html
	Vietnam	—	Regional (land)	3 h	1979–present	National Hydro–Meteorological Service of Vietnam (VNHMS)
	Malaysia (peninsula and Borneo)	—	Regional (land)	3 h	1979–present	Malaysian Meteorological Department (MMD), TMD, and MCGAI
	Philippines	—	Regional (land)	3 h	1979–present	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)
Regional satellite observation	Indonesia (Sumatra and Java)	—	Regional (land)	3 h	1979–present	Meteorological, Climatological and Geophysical Agency, Indonesia (MCGAI)
	APHRODITE (v1204R1)	0.25° lon × 0.25° lat	Asia (land)	Daily	1951–2007	Yatagai et al. (2012)
	GMS T_{BB} (blackbody brightness temperature)	1° lon × 1° lat	59.5°S–59.5°N, 80.5°E–160.5°W	3 h	1980–present	Meteorological Research Institute, Japan
	GMS, <i>GOES-9</i> , and MTSAT	5 km	70°S–70°N, 80°E–150°W	1 h	1979–present	Blersch and Probert (1991) and Meteorological Services Centre Japan (1997)
Global gridded precipitation and rainfall proxy	Tropical Rainfall Measuring Mission (TRMM, 3B42v7)	0.25° lon × 0.25° lat	50°S–50°N, all longitudes	3 h	1998–present	Simpson et al. (1996)
	GOES Precipitation Index (GPI)	1° lon × 1° lat	Global	Daily	1985–95	Susskind et al. (1997)
	Global Precipitation Climatology Project (GPCP, v1.2)	1° lon × 1° lat	Global	Daily	1996–February 2013	Huffman and Bolvin (2013)
	Microwave Sounding Unit (MSU)	2.5° lon × 2.5° lat	Global (ocean)	Daily	1979–October 1996	Spencer (1993)
Global reanalyses (1979–present)	NCEP (National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS))	0.5° lon × 0.5° lat (1° lon × 1° lat from 2004 to 2006)	Global	6 h	6 June 2004–present	Kanamitsu et al. (1991) and Yang et al. (2006)
	ECMWF Interim Re-Analysis (ERA-Interim)	1.5° lon × 1.5° lat	Global	6 h	1979–present	Dee et al. (2011)
	Goddard Earth Observing System, version 5 (GEOS-5) assimilation system	0.667° lon × 0.5° lat	Global	3 h	1979–present	Rienecker et al. (2008)

TABLE 1. (Continued)

Data	Source	Spatial resolution	Spatial domain	Temporal resolution	Data period	Source information
Sea surface temperature	NOAA optimum interpolation sea surface temperature, version 2 (OISSTv2)	1.0° lon × 1.0° lat	Global	Monthly	1979–present	Reynolds et al. (2002)
Daily surface analysis map	NCEP SRRS:					
	Northern Hemisphere surface analysis	—	Northern Hemisphere	12 h	1979–present	SRRS (http://nomads.ncdc.noaa.gov/ncep/NCEP)
	NCEP tropical strip surface analysis and obs	—	Tropical (40°S–40°N)			
	Japan Meteorological Agency TMD	—	Northwestern Pacific 15°S–45°N, 65°E–150°W	6 h 6 h	1979–present 2008–present	http://www.jma.go.jp/en/g3/ http://www.tmd.go.th/en/weather_map.php
	BoM, Australia	—	35°S–30°N, 70°E–180°	12 h	2000–present	http://www.bom.gov.au/australia/charts/archive/
HRF events	Dartmouth Flood Observatory (DFO)*	—	Global	—	1979–present	http://floodobservatory.colorado.edu/
	International Emerging Disaster Database (EM-DAT)	—	Global		1900–present	http://www.emdat.be/
Explosive cyclone	Pressure falling rate of 24 hPa day ⁻¹ NCEP SRRS Northern Hemisphere surface analysis	—	Northern Hemisphere	12 h	1979–present	SRRS (http://nomads.ncdc.noaa.gov/ncep/NCEP)
	Japan Meteorological Agency	—	Northwestern Pacific	6 h	1979–present	http://www.jma.go.jp/en/g3/

* DFO Severity Class: class 1 (large flood events); significant damage to structures or agriculture, fatalities, and/or 1–2 decades-long reported interval, since the last similar event; class 1.5 (very large events); greater than 20 yr but less than 100-yr recurrence interval and/or a local recurrence interval of at 10–20 yr; and class 2 (extreme events); with an estimated recurrence interval greater than 100 yr.

the open ocean, but the southern periphery of the high pressure cell exhibits its maximum northeasterly/easterly flow close to Compo et al.'s (1999) PHS base point in the Philippine Sea.

(ii) The SCS type of cold surge:

The northeast Asian cold surge of the SCS type directs south-southeast from northeastern Asia toward the East China Sea–western North Pacific region around the surface high pressure cell over China. The maximum isotach for this cold surge flow is close to Dongsha Island and Compo et al.'s (1999) SCS base point in the northern South China Sea.

- Issue 2: The flow type of cold surge related to either the westward propagating CSV(HRF) across or the stagnated CSV(HRF) by the demarcation line.

Because the meridional dimension of the South China Sea is over 2000 km, a base point cannot fit all cold surge flows. The interaction of the cold surge flow with CSV(HRF) and the effect of cold surge flow on the CSV(HRF) propagation property across the South China Sea can occur at any latitudinal location. A more practical, but time-consuming, approach is to determine the flow pattern of every cold surge associated with the concerned CSV(HRF) by the following criteria (details are presented in the first part of the supplemental material).

(i) Stagnated/trapped CSV(HRF):

The CSV(HRF) becomes stagnant or trapped, when its 925-hPa vorticity [$\zeta(925 \text{ hPa})$] and vorticity tendency [$\zeta_t(925 \text{ hPa})$] centers are coincident at a longitudinal location of the longitude–time diagrams of these two variables. Then, search is made to find the location of the maximum isotach within the South China Sea. The SCS-type cold surge flow inside the South China Sea is confirmed by the criterion where the meridional wind is less than the zonal wind at 925-hPa [$v(925 \text{ hPa}) > u(925 \text{ hPa})$] (see section 5). The mean longitudinal locations for the maximum isotach at latitudes from the northern to the southern South China Sea form the demarcation line of CSV(HRF) propagation. The identification of this SCS-type cold surge flow is also verified by the Compo et al.'s (1999) criterion in the South China Sea close to the SCS base point and the criterion in northeastern Asia.

(ii) Westward-propagating CSV(HRF):

When the CSV(HRF) center moves across the demarcation line, the flow, which meets the $u(925 \text{ hPa}) > v(925 \text{ hPa})$ criterion at the location of maximum isotach in the South China Sea, is defined as the PHS-type cold surge flow. This identified PHS-type cold surge flow is validated by Compo et al.'s (1999) criterion in the South China

Sea close to the SCS base point and the criterion in northeast Asia.

3) SHALLOW SURFACE TROUGH

The formation mechanisms of the Philippine and Borneo CSV(HRF) are involved with the surface island-chain and the near-equator troughs, respectively. Daily 925-hPa streamline charts, supplemented with NCEP SRRS, JMA, and TMD surface analysis charts, can identify both troughs. An open trough in the low-level streamlines and surface pressure contours adjacent to the Philippines, Taiwan, and Okinawa island chain always reflects the island-chain trough. The near-equator trough is encircled by an east–west elongated cyclonic shear flow, extending eastward from the eastern tropical Indian Ocean, across the tropical South China Sea, to the tropical western Pacific. The formation of these two shallow surface troughs is facilitated by the existence of two climatological troughs. The climatology and spatial structure for these troughs will be presented in section 3.

3. Important elements of the cold-season Southeast Asia circulation

During the cold season, the atmospheric circulation in the tropical western Pacific–South China Sea region is characterized by the winter monsoon; the cyclonic shear flow around the near-equator trough is overlaid by the upper-level anticyclone (Chen 2005). Thus, formation of the cold season weather disturbances over this region generally originates in the lower troposphere. Two preferred regions for the parent CSV(HRF) formation appear over the vicinity of the Philippines and Borneo (Fig. 2).

a. Trough east of the East/Southeast Asia islands

One of three necessary ingredients involved with the formation of the Philippine CSV(HRF) is the island-chain trough. This regional circulation element, which persistently appears in the formation of CSV(HRF), is a shallow surface trough (dashed purple line, Fig. 2) east of the western Pacific island chain. The Asian continental surface high encircled by the 925-hPa streamfunction contours (Fig. 3a) is superimposed with the opposite sign of the vertical pressure velocity ($-\omega$) at 925 hPa; three troughs emerge over the Indian Subcontinent, Indochina, and the ocean east of the North Pacific island chain. The two latter troughs are also well depicted by mean sea level pressure (Fig. 3c). Illustrated by the vertical distribution of $-\omega$ at 20°N on the latitude–height cross sections of eddy streamfunction and geopotential height at 20°N (Figs. 3b), the island-chain

FIG. 3. (a) Winter climatology (DJF) of 925-hPa streamfunction (ψ) superimposed with $-\omega$ (red) (b) vertical cross section from (a) along 20°N , (c) mean sea level pressure (MSLP; contours) superimposed with sea surface temperature (SST; displayed with color scale), and (d) mean ocean current superimposed with SST. The ψ_E contour interval in (b) is divided into groups: $10^6 \text{ m}^2 \text{ s}^{-2}$ for $-12 \times 10^6 < \psi_E \leq 12 \times 10^6 \text{ m}^2 \text{ s}^{-2}$ and $2 \times 10^6 \text{ m}^2 \text{ s}^{-2}$ for $\psi_E > 12 \times 10^6 \text{ m}^2 \text{ s}^{-2}$. Elevation of orography is shaded by the grayscale at the top left of (c).

trough exists below 700 hPa. This trough is often reflected by an open dip south of Taiwan in the JMA surface analysis chart, but its dynamic role in the synoptic development of the East/Southeast Asia weather system is not well understood. The location of this trough line coincides with the Kuroshio (Fig. 3d), but the interaction of the trough and western boundary current has yet to be explained.

b. Near-equator trough and cyclonic shear flow

One of three basic ingredients included in the formation of Borneo CSV(HRF) is the near-equator trough. In Fig. 2, the near-equator trough (red dashed line) migrates equatorward across this island during the cold season. This trough was portrayed with the latitude–height cross sections—streamfunction, vertical motion, and vorticity (see Figs. 11d–f of Chen et al. 2013a)—where the trough extends vertically to the upper troposphere. The positive environmental vorticity and upward motion facilitate the formation of Borneo CSV(HRF). Additionally, the southward migration of this near-equator trough toward Java is a factor to the formation of Java HRF events, with or without Borneo CSVs involvement.

The near-equator trough is encircled by the east–west elongated cyclonic shear flow, which will be shown later in the 925-hPa streamline charts for all Borneo

CSV(HRF) formations. This shear flow may be intensified by the SCS-type cold surge flow around western Borneo. The intensification of this shear flow has two important implications. First, the deepening of the near-equator trough across Borneo by this shear flow intensification can facilitate the Borneo CSV(HRF) formation. Second, the westward advection of vorticity of CSV(HRF), which can be reduced by this shear flow intensification, hinders the westward propagation of Borneo CSV(HRF). In other words, the cyclonic shear flow of the near-equator trough plays an important role not only in the CSV(HRF) formation, but also in determining on which side of the South China Sea the HRF event may occur.

4. Synoptic characteristics of the formation of CSV(HRF)

Based on the locations and trajectories linked to formation locations of their parent CSV(HRF) (Fig. 2), the HRF events are divided into 10 groups in Table 2. These CSV(HRF) primarily form over the vicinity of the Philippines and Borneo, except four Java HRF events formed without parent CSV(HRF). The CSV(HRF) trajectories show HRF events west of the South China Sea may develop from both the Philippine and Borneo CSV(HRF). In contrast, HRF events east of the South

TABLE 2. Formation preference of parent CSV(HRF) and their corresponding HRF cyclones/events. The preferred types of cold surge, time of day, and region for CSV(HRF) formation. The occurrence number of HRF cyclone/events and the time period covering these events are also included. All 181 HRF cyclone/events identified by DFO over the seven cold-season rainfall centers in both sides of the SCS are developed from CSV(HRF), except three HRF events in Java (out of 23 during 1992–2012) are directly formed through the deepened/intensified the near-equator trough by the strong SCS type of cold surge flow, and one HRF event developed by a CSV(HRF) formed in the Celebes Sea.

Region	Parent CSV(HRF)(preferred type of cold surge, preferred formation time)	HRF cyclone/event (number, period)
West of the SCS, developed from westward propagating CSV(HRF)	Philippine (PHS type, 0600 UTC)	Central Vietnam (37, 1979–2012)
	Philippine (PHS type, 0600 UTC)	Peninsular Malaysia (18, 1979–2012)
	Philippine (PHS type, 0600 UTC)	Southeastern Sumatra (4, 1992–2012)
	Borneo (SCS type, 0000 UTC)	Peninsular Malaysia (17, 1979–2012)
	Borneo (SCS type, 0000 UTC)	Southeastern Sumatra (7, 1992–2012)
East of the SCS, developed from trapped CSV(HRF)	Philippine (PHS type, 0600 UTC)*	Northern Philippines (18, 1992–2012)
	Philippine (PHS type, 0600 UTC)*	Southern Philippines (23, 1992–2012)
	Borneo (in situ) (SCS type, 0000 UTC)*	Borneo (38, 1979–2012)
	Borneo (in situ) (SCS type, 0000 UTC)*	Java (19, 1992–2012)
	Java (in situ) (SCS type)	Java (4, 1992–2012)

* Four groups of CSV(HRF) are used to define the demarcation line of propagation for these CSV(HRF).

China Sea may develop either from the Philippine or in situ Borneo CSV(HRF). Thus, the development of HRF events from their parent CSV(HRF) may be reclassified into three groups: 1) westward-propagating CSV(HRF) from a distant region, 2) stagnated CSV(HRF) propagating from a nearby vicinity, and 3) trapped CSV(HRF). To avoid redundancy, the synoptic analysis for the formation of parent CSV(HRF) and their ensuing HRF cyclones/events over every rainfall center around the South China Sea is available online (http://eamex.iastate.edu/publication/synoptic_analysis_181HRF.pdf). The salient synoptic features, which emerge from the formations of different types of CSV(HRF), will be highlighted with individual typical examples.

a. Westward-propagating CSV(HRF) across the South China Sea

1) THE PHILIPPINE CSV(HRF) DEVELOPED INTO A PENINSULAR MALAYSIA HRF CYCLONE/ EVENT

As shown in Fig. 2, there are three groups of HRF cyclones/events (37 in central Vietnam, 18 in peninsular Malaysia, and 4 in southeastern Sumatra) that develop from the Philippine CSV(HRF). Although Chen et al. (2012a,c) analyzed central Vietnam HRF events, a typical peninsular Malaysia HRF event (9 November 2010) is selected in this study to examine whether salient features of the latter two groups behave as the central Vietnam cases (listed in the introduction). The rainfall rate for this peninsular Malaysia HRF event reaches 292 mm day^{-1} at Kota Bharu (WMO identifier 48615). The salient synoptic features of this development are shown in Figs. 4a–c highlighted as follows:

- The 925-hPa streamline chart at 0600 UTC 4 November 2010 (Fig. 4a), verified by the JMA surface analysis chart, exhibits a surface island-chain trough (golden line) emerging east of the Philippines and Taiwan. A CSV(HRF) is formed in the southern Philippines through the interaction of an easterly wave (red line, Fig. 4a) with the northeast Asian cold surge flow and the island-chain trough.
- Occurrences of the peninsular Malaysia HRF event and the northwestern Pacific explosive cyclone (marked in Fig. 4c) synchronize.
- Maximum intensities (Fig. 14 of Part II) across the HRF cyclone/event, northeast Pacific explosive cyclone, and tropical trade easterlies take place simultaneously when this HRF event occurs.
- The basic characteristics (size, speed, and rainfall) of this Philippine CSV(HRF) are smaller than the corresponding HRF cyclone/event.

These synoptic features are common to formation of the CSV(HRF), which develops into the peninsular Malaysia and Sumatra HRF cyclones/events, as are all identified central Vietnam HRF cyclones/events.

Additional synoptic features identified in the formation of the Philippine CSV(HRF) linked to the three rainfall centers west of the South China Sea are the following:

- The island-chain surface trough is an indispensable synoptic element to the formation of the Philippine CSV(HRF).
- The preferred formation time of the Philippine CSV(HRF) is 0600 UTC (1400 LST; Fig. 4b). The

FIG. 4. (a) The 925-hPa streamline chart superimposed with TRMM precipitation at 0600 UTC 4 Nov 2010 for CSV(HRF) formed in the Philippine Sea. (b) Surface pressure (p_s , dashed red line) and its diurnal ($\tilde{p}_s$) and semidiurnal ($\hat{p}_s$) components (solid red line) combined with the CSV(HRF) formation time (red arrow). (c) The Philippine CSV(HRF) in (a) propagated westward and developed into a HRF event in peninsular Malaysia at 1200 UTC 9 Nov 2010. (d)–(f) As in (a)–(c), except showing (d) the CSV(HRF) formation time at 0000 UTC 5 Dec 2004 in Borneo that then (f) propagated westward and developed into a peninsular Malaysia HRF event at 0000 UTC 10 Dec 2004. (e) Time series of p_s (dashed black line) and $\tilde{p}_s + \hat{p}_s$ (solid black line) at Brunei Airport (WMO identifier 96315), Borneo.

FIG. 5. Global distributions for $\tilde{p}_s + \hat{p}_s$ at (a) 0600 UTC 4 Nov 2010 (Philippine to Malaysia case) and (b) 0000 UTC 5 Dec 2004 (Borneo to Malaysia case) correspond to Figs. 4b and 4e, respectively.

minimum value of the semidiurnal surface pressure component propagates across the Maritime Continent [Fig. 5a, predicted by Lindzen (1971)].

The differences in the synoptic features of the formation and development of the three CSV(HRF) groups are the following:

- (i) Trajectories of the Philippine CSV(HRF) to peninsular Malaysia and southeastern Sumatra are longer than those to central Vietnam, and so are the traveling times (7.5 days for the former two groups, and 4.5 days for the latter group).
- (ii) The seasonal march of the Southeast Asia monsoon circulation leads to the southward migrations of the Philippine CSV(HRF) formation, and the northeasterlies north of the near-Equator trough.

2) BORNEO CSV(HRF) DEVELOPED INTO PENINSULAR MALAYSIA HRF CYCLONE/ EVENT

From Table 2, half (17) of peninsular Malaysia and seven southeastern Sumatra HRF cyclones/events developed from Borneo CSV(HRF). The synoptic features for development of a typical Borneo CSV(HRF) into a peninsular Malaysia HRF cyclone/event are shown in the lower panels of Figs. 4d–f:

- (i) During the deep winter, the near-equator trough migrates farther south across Borneo (Fig. 2). The strong SCS-type cold surge flow intensifies the cyclonic shear flow around Borneo and deepens this near-equator trough. The interaction among these synoptic elements facilitates the Borneo

CSV(HRF) formation at 0000 UTC 5 December 2008 (Fig. 4d).

- (ii) Five days later, the SCS-type cold surge flow yields to a new PHS-type cold surge flow (Fig. 4f). The easterlies of this cold surge flow allow this Borneo CSV(HRF) to propagate westward to peninsular Malaysia and form a HRF cyclone/event on the near-equator trough. This HRF event produced a rainfall rate of 296 mm day^{-1} measured at the Butterworth (WMO identifier 48602).
- (iii) Occurrences of the peninsular Malaysia HRF cyclone/event and the northwestern Pacific explosive cyclone (Fig. 4f) are synchronized and accompanied with the simultaneous occurrences of the maximum easterlies of the peninsular Malaysia HRF and westerlies of the northwestern Pacific explosive cyclone and tropical trade easterlies (Fig. 14 of Part II).
- (iv) The basic characteristics for this CSV(HRF) and its corresponding HRF cyclone/event behave the same way as that for the Philippine CSV(HRF) and its HRF cyclone/event.

These synoptic features are typical to both the peninsular Malaysia and southeastern Sumatra HRF cyclones/events developed from Borneo CSV(HRF), and the three groups of HRF cyclone/events developed from the Philippine CSV(HRF).

Some significant differences of synoptic features exist between HRF cyclones/events developed from the Philippine and Borneo CSV(HRF):

- (i) The near-equator trough in the Borneo CSV(HRF) formation replaces the island-chain trough in the Philippine CSV(HRF) formation, except the latter formation is not involved with an easterly wave.

FIG. 6. The 925-hPa streamline chart superimposed with TRMM precipitation (a) at 0600 UTC 1 Nov 2007 of CSV(HRF) formed in the Philippine Sea, then propagated westward and (b) developed into a Luzon HRF event at 0600 UTC 4 Nov 2007. (c),(d) As in (a),(b), but for the CSV(HRF) formed at 0600 UTC 9 Feb 2012 in the Philippine Sea and a Mindanao HRF event at 1200 UTC 11 Feb 2012.

- (ii) The formation time of day for the majority (78%) of Borneo CSV(HRF) is 0000 UTC (Fig. 4e), when surface pressure (p_s) and the sum of the diurnal and semidiurnal components ($\bar{p}_s + \hat{p}_s$) exhibit their minimum values. Figure 5b shows the maximum value of $\bar{p}_s + \hat{p}_s$ (essentially contributed by $\hat{p}$) appearing over the Maritime Continent (Fig. 5b). According to Houze et al. (1981), this 6-h phase difference is likely caused by the morning convection stimulated by the collision of the cold morning downslope flow in western Borneo with the strong northerlies of the SCS-type cold surge flow.
 - (iii) The westward propagation of the Borneo CSV(HRF) to peninsular Malaysia is attributed to the transition of the strong SCS-type cold surge flow [five days after the Borneo CSV(HRF) formed] to a PHS-type cold surge flow.
- b. *Philippine CSV(HRF) stagnated at the east side of the South China Sea*
- 1) THE NORTHERN PHILIPPINES
- Most of the northern Philippine HRF events, which occur north of 10°N (Fig. 2d), develop from Philippine CSV(HRF) in the central Philippine Sea. Major synoptic features related to the formation of central Vietnam HRF events and their parent CSV(HRF) also appear in the northern Philippine HRF events. However, some unique synoptic features of the northern Philippine HRF case include the following:
- (i) The Philippine CSV(HRF) (Fig. 6a) is formed by the interaction of an easterly wave with the surface

island-chain trough and a PHS-type cold surge at 0600 UTC 1 November 2007.

- (ii) The traveling time ($\sim < 3$ days) for this Philippine CSV(HRF) to form a Philippine HRF event is shorter than the time for the central Vietnam HRF events to form. This event produced a rainfall rate of 285 mm day^{-1} at the Baler radar (WMO identifier 98334).
- (iii) The northeast Asian surface low [coupled with the cold surge flow, which forms the Philippine CSV(HRF)] develops into a northwestern Pacific explosive cyclone. Occurrence of this cyclone synchronizes with the northern Philippine HRF event.
- (iv) The short traveling time of the parent Philippine CSV(HRF) is caused by the fact the corresponding HRF cyclone/event is prevented from propagating westward by the strong northerlies of a SCS-type cold surge flow (Fig. 6b).

2) THE SOUTHERN PHILIPPINES

The majority of the southern Philippine HRF events, which occur south of 10°N , develop from the Philippine CSV(HRF) south of 10°N (Fig. 2d). These CSV(HRF) are formed by the same mechanism at 0600 UTC as the northern Philippine CSV(HRF) (Fig. 6a). Synoptic features related to formations of CSV(HRF) and the HRF event in the southern Philippines include the following:

- (i) Being formed close to the near-equator trough (Fig. 6c), this southern Philippine CSV(HRF) eventually merges with this trough (Fig. 6d) to form the southern Philippine HRF event and produce a rainfall rate of 278 mm day^{-1} at the Davao Airport (WMO identifier 98753).
- (ii) It takes only two days for this southern CSV(HRF) to propagate from the southern Philippine Sea to Mindanao and form a HRF event, which synchronizes with the occurrence of a northwestern Pacific explosive cyclone (Fig. 6d).
- (iii) This southern Philippine HRF cyclone/event is embedded in the near-equator trough and prevented from propagating westward by the strong northerlies of a SCS-type cold surge flow (Fig. 6d).

c. Tropical Borneo CSV(HRF) on the east side of the South China Sea

During the deep winter, the near-equator trough migrates across Borneo to the equator and facilitates the Borneo CSV(HRF) formation, when the SCS-type cold surge flow appears near western Borneo. Shown in Table 2, 38 Borneo and 19 Java HRF events develop from Borneo CSV(HRF). Additionally, three Java HRF

events develop from the direct interaction of the SCS-type cold surge flow with the near-equator trough, and another one develops from the Celebes Sea CSV(HRF). Despite the difference in the origin of their parent CSV(HRF), developments of Borneo and Java HRF cyclones/events exhibit the same basic synoptic features of the HRF cyclones/events west of the South China Sea and the Philippine HRF cyclones/events. Therefore, we only highlight those special features, which differ from those for the HRF cyclones/events west of the South China Sea and the Philippines.

1) TRAPPED BORNEO CSV(HRF) DEVELOPED INTO BORNEO HRF EVENT

- (i) A Borneo CSV(HRF) is formed at 0000 UTC 18 December 2011 through the deepening of the near-equator trough by a SCS-type cold surge flow around western Borneo. The basic elements required for this CSV(HRF) formation are the near-equator trough, the SCS-type cold surge flow, and Borneo orography (Fig. 7a).
- (ii) The formation time for this Borneo CSV(HRF) is 0000 UTC (which is different from the Philippines, at 0600 UTC). Houze et al. (1981) argue that minimum surface pressure appears when the cold morning downslope flow collides with strong easterlies from a SCS-type cold surge flow.
- (iii) The 25 December 2011 Borneo HRF cyclone/event, developed from the trapped CSV(HRF) (Fig. 7b), produced a rainfall rate of 282 mm day^{-1} at Sibu (WMO identifier 96421).

2) TRAPPED BORNEO CSV(HRF) DEVELOPED INTO A JAVA HRF CYCLONE/EVENT

Developments of Java HRF events are classified into two groups—with and without Borneo CSV(HRF). The synoptic condition of a typical case for each group is shown in Fig. 7.

(i) Java HRF cyclone/event developed with a Borneo CSV(HRF)

The synoptic condition for the parent Borneo CSV(HRF) formation (at 0000 UTC 15 January 2007) of the Java HRF event (23 January 2007) (Fig. 7c) resembles that for the Borneo HRF event (Fig. 7a)—the interaction among the SCS-type cold surge flow, the near-equator trough, and Borneo orography are presented. To save space, the synoptic development of this Java HRF cyclone/event is posted online (http://eamex.iastate.edu/publication/synoptic_10HRF.pdf). This Java HRF cyclone/event centered on western Borneo produced a rainfall rate of 340 mm day^{-1} at the Tanjung Priok

FIG. 7. The 925-hPa streamline superimposed with TRMM precipitation for (a) a CSV(HRF) formed at 0000 UTC 18 Dec 2011 in Borneo and (b) developed into a Borneo HRF event Borneo at 0000 UTC 25 Dec 2011. (c) A Java HRF event formed by Borneo CSV(HRF) and (d) the circulation departure between (c) and the composite of all Borneo HRF events. (e),(f) As in (c),(d), but for the Java HRF events developed without a Borneo CSV(HRF).

subdistrict of Jakarta (WMO identifier 96741). Although the rainfall center for this HRF event appears only across the narrow Java Sea, some major difference is expected between the synoptic conditions of the Java and Borneo HRF event. This difference is illustrated by the departure of the 925-hPa wind vector and

precipitation $\{\Delta[V(925 \text{ hPa}), P]; \text{Fig. 7d}\}$, the difference between $[V(925 \text{ hPa}), P]$ for this Java HRF event (Fig. 7c), and the composite $[V(925 \text{ hPa}), P]$ for all Borneo HRF events. An anomalous cyclonic circulation around the Java HRF rainfall center emerges. The convergence of water vapor flux is enhanced to maintain

the Java HRF rainfall center by the southward migration of the near-equator trough.

(ii) *Java HRF cyclone/event developed without a Borneo CSV(HRF)*

Three Java HRF events develop from the direct interaction of the SCS-type cold surge flow with the near-equator trough without the presence of a Borneo CSV(HRF). The synoptic conditions of a Java HRF event (29 January 2002) are shown in Fig. 7e. The near-equator trough is deepened by the strengthening of the cyclonic shear flow around western Borneo by a well-organized SCS-type cold surge flow, and enables this cyclonic flow to move across Java and reach Christmas Island. This synoptic development can be perceived through the anomalous cyclonic flow pattern around Java depicted by $\Delta[V(925 \text{ hPa}), P]$ on 29 January 2002 (Fig. 7f), the difference between $[V(925 \text{ hPa}), P]$ on 29 January 2002, and composite $[V(925 \text{ hPa}), P]$ of 19 Java HRF events. This synoptic change leads to the formation of this Java HRF event.

d. *Summary*

Most salient synoptic features identified for the development of CSV(HRF) into central Vietnam HRF events are common to individual typical cases of the 10 groups of CSV(HRF) presented in Table 2. Additional to these features, other newly identified features are classified into three components, listed here.

1) **FORMATION MECHANISM OF CSV(HRF)**

- The Philippine CSV(HRF) are formed by the interactions of an easterly wave with the PHS-type cold surge flow and the surface island-chain trough.
- The Borneo CSV(HRF) are formed by the interactions among the SCS-type cold surge flow, the near-equator trough, and Borneo orography.
- The preferred formation time of the Philippine CSV(HRF) is 0600 UTC, coincident with the local time of the minimum semidiurnal surface pressure. For a Borneo CSV(HRF), the preferred formation time is 0000 UTC, which matches well with the morning convection by the interaction of the cold morning downslope flow with the SCS-type cold surge flow.

2) **PROPAGATION PROPERTIES OF CSV(HRF)**

- Two types (PHS and SCS) of cold surge flows determine the propagation properties of CSV(HRF) across the South China Sea. The Philippine (Borneo) CSV(HRF) propagate (stagnate) westward (in situ) to the west (east) of the South China Sea when the PHS (SCS)-type cold surge flow exists across this sea.

- The near-equator trough exhibits an equatorward migration from late fall to deep winter. The intensification of the cyclonic shear flow around this trough hinders the westward propagation of the Philippine and Borneo CSV(HRF) across the South China Sea.

3) **FORMATION OF HRF CYCLONES/EVENTS**

- The formation locations of HRF cyclones/events are determined by the propagation properties of their parent CSV(HRF).
- The intensity (deepening) of the near-equator trough south of the equator facilitates the formation of Java HRF events.

The next two sections are devoted to explore whether these newly identified synoptic features for the formation of individual typical CSV(HRF) in this section are common to the corresponding groups of CSV(HRF).

5. Formation mechanisms of CSV(HRF)

a. *Preferred mechanism and geographic location*

The formation mechanisms of the Philippine and Borneo CSV(HRF) were synoptically identified in section 4. One may question whether these two formation mechanisms work for all identified CSV(HRF) in their corresponding group shown in Figs. 2a–e.

The following definitions for easterly waves, the island-chain trough, and the PHS-type cold surge flow presented in section 2, 100 Philippine CSV(HRF) (related to 59 HRF events west of the South China Sea, and another 41 HRF events east of this sea) are verified/validated against all necessary and available charts to determine if the formation mechanism of the Philippine CSV(HRF) works for all of them. As confirmed in Table 3, all of these CSV(HRF) are generated by the same mechanism.

Borneo CSV(HRF) lead to the formation of HRF events, which occur not only in Borneo (38 in situ) and Java (19) during December–February, but also over peninsular Malaysia (17) and Sumatra (7) during November–December. Regardless of the postformation development of Borneo CSV(HRF) into HRF events in remote or in situ regions, one may question whether all 81 Borneo CSV(HRF) are formed by the same mechanism. This question is also clarified in Table 4, except for four Java HRF events develop without Borneo CSV(HRF).

Formation locations for both Philippine and Borneo CSV(HRF) exhibit their geographic preference in Fig. 2. To facilitate confirmation of the finding, formation locations for these two groups of CSV(HRF) against the December–February 925-hPa streamline charts are shown in Fig. 8. Tables 3 and 4 reveal the

TABLE 3. Occurrence season, related rainfall center, propagation property, and synoptic elements required for the formation mechanism of the Philippine CSV(HRF).

Season	October–November	November–December	November–January	October–December	December–February
Rainfall center (No. of HRF events)	Central Vietnam (37)	Peninsular Malaysia (18)	Sumatra (4)	Northern Philippines (18)	Southern Philippines (23)
Island-chain trough (T)	All 37 events T	All 18 events T	All 4 events T	All 18 events T	All 23 events T
Easterly wave (E)	All 37 events E	All 18 events E	All 4 events E	All 18 events E	All 23 events E
Cold surge PHS-type (P)	All 37 events P	All 18 events P	All 4 events P	All 18 events P	All 23 events P
Propagation property of parent CSV(HRF)	Westward	Westward	Westward	Westward	Westward

newly identified synoptic element needed for the formation of Philippine CSV(HRF) is the island-chain trough adjacent to the Philippines and for Borneo CSV(HRF) this required element is the near-equator trough across Borneo. As presented in [section 3](#), the climatological location of the island-chain trough exists east of the Philippines from late fall to early winter and the climatological location of the near-equator trough appears longitudinally across Borneo during winter. The climatological locations for these two troughs are conducive to the synoptic developments of these two troughs in the vicinity of the Philippines and Borneo, respectively, and result in the geographic preference for the formation of these two CSV(HRF) groups.

b. Preferred time and cold surge flow type

As observed in [section 4](#), 1) the preferred formation time of the Philippine CSV(HRF) is 0600 UTC under the influence of the PHS-type cold surge flow, and 2) the Borneo CSV(HRF) forms at 0000 UTC with the impact of the SCS-type cold surge flow. Can all 181 CSV(HRF) formations over these two regions have a clear distinction in the preferred time and type of cold surge flow? The maximum vorticity of CSV(HRF) is used as an indicator of this vortex strength whose magnitude is projected on the radius of a 24-h clock for the Philippine ([Fig. 9a](#)) and Borneo ([Fig. 9b](#)) CSV(HRF). Three basic characteristics [magnitude of maximum vorticity $\zeta(850\text{ hPa})$, formation time, and the cold surge flow type involved with the CSV(HRF) formation] for every identified CSV(HRF) are projected on [Figs. 9a and 9b](#). Another 261 Philippine nondeveloped (NOD) CSV [CSV(NOD)] and 266 Borneo CSV(NOD) are also projected on these two clocks for comparison with CSV(HRF).

The salient features that emerge from [Figs. 9a and 9b](#) are explained below.

- 1) A great majority (78%) of the Philippine CSV(HRF) form at 0600 UTC, under the PHS type of cold surge flow, but 11% form at 0300 UTC and another 11% form at 0900 UTC. The preferred CSV(HRF) formation time for this group is during the local afternoon. The Philippine CSV(NOD) do not show any preferred formation time of day. The maximum $\zeta(850\text{ hPa})$ magnitudes for CSV(NOD) are significantly smaller than CSV(HRF).
- 2) The majority (59%) of the Borneo CSV(HRS) form at 0000 UTC, while 41% form at 2100 UTC. Both preferred CSV(HRF) formation times for this group are during the local morning. The Borneo CSV(NOD) formation shows no preferred time of day. The maximum $\zeta(850\text{ hPa})$ magnitudes of CSV(NOD) are also smaller than CSV(HRF).

TABLE 4. As in Table 3, but for Borneo CSV(HRF).

Season	November–December	December–January	December–February	January–February
Rainfall center (No. of HRF events)	Peninsular Malaysia (17 from Borneo)	Sumatra (7 from Borneo)	Borneo (38 in situ)	Java (19 from Borneo)
Near-equator trough (T)	All 17 events T	All 7 events T	All 38 events T	19 events T and 4 events T without Borneo CSV(HRF)
Orography (O)	All 17 events O	All 7 events O	All 38 events O	19 events O and 4 events O without Borneo CSV(HRF)
Cold surge SCS-type (S)	All 17 events S	All 7 events S	All 38 events S	19 events S and 4 events S without Borneo CSV(HRF)
Propagation property of parent CSV(HRF)	Westward	Westward	Stagnated	Stagnated

The preferred time and cold surge flow type of CSV(HRF) formation shown in Figs. 9a–c have the following implications:

- 1) The preferred formation time for the Philippine CSV(HRF) at 0600 UTC (Fig. 9a), local afternoon, is attributed to two factors: (i) The sea surface temperature (Fig. 3c) over the western tropical Pacific is warmer than the remaining tropical Pacific. The daily shortwave heating facilitates the afternoon convection (e.g., Nitta and Sekine 1994). (ii) The surface pressure in the vicinity of the Philippines is primarily deepened by the semidiurnal component (Fig. 4b) to reach a minimum at 0600 UTC (Fig. 5a) and trigger the CSV(HRF) formation. This argument is supported by the minimum Δp_s at the Philippine surface stations close to CSV(HRF) centers (Fig. 9c).
- 2) The preferred formation time for Borneo CSV(HRF) is during the morning (2100–0000 UTC) (Fig. 9b), which is about 6–7 h ahead of the Philippine CSV(HRF) formation time, approximately a half-cycle of semidiurnal surface pressure. The surface pressure over Borneo at 0000 UTC reaches its maximum primarily due to the semidiurnal p_s component (Fig. 9c). The preferred formation time of a Borneo CSV(HRF) may be well attributed to the Houze et al. (1981) mechanism explained previously.

6. Propagation properties of CSV(HRF)

Analyzing the rain-producing weather systems related to the winter rainfall in Malaysia, Chen et al. (2013a) found the propagation properties for Borneo CSV(HRF) are regulated by the cold surge flow pattern in the South China Sea. The PHS-type cold surge flow with strong well-organized easterlies makes the westward propagation of these CSV(HRF) and HRF cyclones/events possible. In contrast, the stagnation of these disturbances is caused by the SCS-type cold surge flow with strong northerlies. All HRF events in the rainfall centers

west of the South China Sea, and over both the northern and southern Philippines develop from the Philippine CSV(HRF). Can the two types of cold surge flows regulate the propagation properties for these CSV(HRF)?

The vertical structure for the winter circulation in the western tropical Pacific is illustrated by the latitude–height cross section of the eddy streamfunction and vorticity (ψ_E, ζ) at 124°E during October–November in Fig. 10a, including a location mark for the island-chain trough. The monsoon circulation structure is characterized by a vertical phase change in the midtroposphere. The vertical extent of a CSV(HRF) is limited by the upper-level anticyclone, as illustrated for the case of 14 October 2008 shown in Fig. 10b. Thus, the CSV(HRF) is primarily steered westward by the low-tropospheric flow.

FIG. 8. Formation location for October–February of the Philippine CSV(HRF) (red dots) against the island-chain trough (purple dashed line) and Borneo CSV(HRF) (gold dots) against the near-equator trough (red dashed line) superimposed on the December–February 925-hPa streamline chart.

FIG. 9. (a) The formation time of the Philippine CSV(HRF) determined with the maximum vorticity of this vortex depicted by the streamline chart of the GEOS-5 3-h reanalysis, and (b) the formation time of CSV(HRF) in Borneo. (c) Formation times of CSV(HRF) in both the vicinity of the Philippines and Borneo are determined by the departure of the minimum p_s from the daily-mean p_s at the surface station closest to the vortex center.

a. Regulation of the CSV(HRF) propagation property by the cold surge flow type

1) DEMARCATION LINE OF THE CSV(HRF) PROPAGATION PROPERTIES

To determine the propagation activity of CSV(HRF), a demarcation line in the South China Sea is defined to divide CSV(HRF) into two groups—westward propagating and stagnant. Then, two sets of simple (u , v) at 925 hPa scatter diagrams of cold surge flow are presented to illustrate how these two types of cold surge flows affect the propagation properties for nine groups of CSV(HRF).

(i) Definition of the propagation demarcation line

The following steps are adopted to define this demarcation line in the South China Sea:

- 1) Indicated by the longitude–time diagram of its $\zeta(925 \text{ hPa})$ center, a CSV(HRF) reduces the westward propagation speed until its $\zeta(925 \text{ hPa})$ and $\zeta_r(925 \text{ hPa})$ centers spatially coincide. Register the time and location [solid triangle with color corresponding to the location of the associated cold surge's maximum $v(925 \text{ hPa})$] for this coincidence (Fig. 11a).

FIG. 10. (a) The latitude–height cross section of the October–November eddy streamfunction (ψ_E ; contour) superimposed with vorticity (ζ ; color in red/blue) at 120°E averaged over 1979–2012. The location of the island-chain trough is indicated by the thick tick mark at the bottom center. (b) As in (a), but for a CSV(HRF) formed in the vicinity of the Philippines on 14 Oct 2008 and propagated to central Vietnam.

- 2) Identify the location of the associated cold surge flow's maximum speed $|\mathbf{V}(925 \text{ hPa})|$ in the South China Sea, when the CSV(HRF) stops its westward propagation observed in step 1.
 - 3) Register all identified locations of the cold surge flow's maximum speed in step 2 with crosses in Fig. 11a for all 98 stagnant CSV(HRF) (Table 2). The demarcation line between the westward-propagating and stagnant CSV(HRF) is defined by the mean-longitudinal locations of maximum $v(925 \text{ hPa})$ of the associated SCS-type cold surge flows.
- (ii) Scatter diagrams of the (u, v) components at 925 hPa at the location of maximum cold surge flow for both westward-propagating and stagnant CSV(HRF)

Locations of maximum cold surge flow speed are registered when CSV(HRF) centers for the five westward propagation groups (Table 2) reach the propagation

demarcation line. The positive $\zeta_t(925 \text{ hPa})$ centers for CSV(HRF) are west of their positive $\zeta(925 \text{ hPa})$ centers. The (u, v) components at 925 hPa of the identified locations of maximum cold surge flow speed for these groups of CSV(HRF) are shown in the scatter diagrams (Fig. 11b). On the other hand, the scatter diagrams for (u, v) at 925 hPa at locations of maximum cold surge flow speed for the four stagnated/trapped CSV(HRF) groups at the propagation demarcation line are shown in the scatter diagrams in Fig. 11c. A positive $\zeta_t(925 \text{ hPa})$ center for CSV(HRF) coincides with its $\zeta(925 \text{ hPa})$ center.

The following salient features characterize these two sets of (u, v) at 925 hPa scatter diagrams:

- 1) For all westward-propagating CSV(HRF) (Fig. 11b), the $u(925 \text{ hPa})$ components for maximum cold surge flow speed (left-hand panel) are easterlies, while the accompanying $v(925 \text{ hPa})$ components (right-hand panel) are northerlies. The magnitude $u(925 \text{ hPa})$ for every identified maximum cold surge flow speed is larger than $v(925 \text{ hPa})$. The cold surge flow that allows CSV(HRF) to propagate westward across the propagation demarcation line is the PHS type.
- 2) For the stagnant CSV(HRF) (Fig. 11c), the $u(925 \text{ hPa})$ components of the maximum cold surge flow speed associated with these CSV(HRF) (left-hand panel) are all easterlies, while the $v(925 \text{ hPa})$ components (right-hand panel) are all northerlies. The magnitude for the latter component is larger than the former. All cold surges concerned here are the SCS type.

2) COMPOSITE $(\mathbf{V}, |\mathbf{V}|)$ AT 925-HPA STREAMLINE CHARTS WHEN CSV(HRF) FORM

To obtain a better perspective of how the cold surge flow patterns regulate the CSV(HRF) propagation property, the composite $(\mathbf{V}, |\mathbf{V}|)$ at 925 hPa streamline charts for nine groups of CSV(HRF) are shown in Figs. 12a–i (the statistical significances for all nine composite streamline charts are shown in second part of the supplemental material). Salient features for these composite streamline charts are:

- (i) Despite formation locations for all five groups of westward-propagating CSV(HRF), the composite flow patterns (Figs. 12a–e) exhibit the PHS-type cold surge flow pattern with strong easterlies across the South China Sea.
- (ii) The composite flow patterns for all four groups of stagnant CSV(HRF) (Figs. 12f–i) are characterized by strong northerlies of the SCS-type cold surge.

The strong easterly flow for the first five groups of CSV(HRF) facilitates the westward propagation of these vortices, while the strong northerly flow for the

FIG. 11. (a) Location of CSV(HRF) trapped by the cold surge flow in the South China Sea is marked by a triangle, while the location of the maximum northerly of the associated cold surge flow is denoted by a cross. Then, the polynomial least squares fit with the cubic (third degree) function (Kincaid and Cheney 2002) is adopted to generate the demarcation line of propagation vs nonpropagation CSV(HRF). A black solid line depicts this demarcation line. (b) When centers of five groups of westward propagating CSV(HRF) reach the demarcation line, the maximum zonal and meridional wind speeds for this cold surge flow in the South China Sea are presented. (c) The 925-hPa zonal and meridional wind speeds of cold surge at the maximum northerly location for four groups of trapped CSV(HRF). Uppercase characters shown in both sides of (b) are the abbreviations: CV (Philippines–central Vietnam), PM (Philippines–Malaysia), BM (Borneo–Malaysia), PS (Philippines–southeastern Sumatra), and BS (Borneo–southeastern Sumatra), while abbreviations in (c) are NP (Philippine Sea–northern Philippines), SP (Philippine Sea–southern Philippines), BO (Borneo in situ), and JV [Java with Borneo CSV(HRF)].

FIG. 12. The composite 925-hPa streamline charts superimposed with the isotach wind speed for nine groups of CSV(HRF). The dates used for the composite procedure for each CSV(HRF) group are those used in Figs. 11b,c to determine whether CSV(HRF) propagates across this demarcation line or becomes stagnated east of this line.

FIG. 13. (a)–(i) The center location of vorticity (ζ ; red dots) vs that of vorticity tendency [ζ_t ; blue crosses in (a)–(e) and triangles in (f)–(i)] for nine CSV(HRF) groups. Dates of CSV(HRF) processed for this figure are exactly the same as in Figs. 11b,c.

second four groups of CSV(HRF) prevents them from propagating westward. The cold surge flow type determines the steering mechanisms for these two groups of CSV(HRF).

b. Vorticity budget analysis

1) STATISTICS OF (ζ , ζ_t) AT 925 hPa

According to the vorticity budget equation, the total vorticity tendency is caused by the imbalance among the dynamic processes included. The spatial relationship between vorticity and its tendency center is used to

illustrate the propagation property of a weather disturbance. This approach, adopted by Chen et al. (2013a), discloses the mechanism, which allows Borneo CSV(HRF) to propagate westward or become stagnant. Statistics of the spatial relationship between ζ (925 hPa) and ζ_t (925 hPa) are shown in Figs. 13a–i, when CSV(HRF) reach the demarcation line of propagation (Fig. 11a). The scatter diagrams for ζ (925 hPa) (red dots) and ζ_t (925 hPa) (blue crosses) centers on five PHS CSV(HRF) groups shown in Figs 13a–e, while ζ (925 hPa) (red dots) and ζ_t (925 hPa) (blue triangles) for four SCS CSV(HRF) groups are

FIG. 14. As in Fig. 12, except the composite streamline chart is superimposed with vorticity (ζ ; shading) and vorticity tendency (ζ_t ; red and blue colors) at 925 hPa. The composite procedure for this figure is the same as in Fig. 12.

displayed in Figs. 13f–i. The ζ_t (925 hPa) centers for five former CSV(HRF) groups are west of the corresponding ζ (925 hPa) centers, while those for four latter CSV(HRF) groups are spatially in phase with the corresponding ζ (925 hPa) centers. The spatial relationship between the ζ_t (925 hPa) and ζ (925 hPa) centers for the first five groups allows each CSV(HRF) to propagate westward, but not for any in the second four groups.

2) COMPOSITE CHARTS OF ($\mathbf{V}$, ζ , ζ_t) AT 925 hPa

Following Figs. 12a–i, the composite 925-hPa streamline charts for nine groups of parent CSV(HRF) superimposed with (ζ , ζ_t) at 925 hPa are shown in Figs. 14a–i (the statistical significances for all nine streamline charts are shown in the second part of the supplemental material). The positive ζ_t (925 hPa) centers appear west of the ζ (925 hPa) centers for five groups of

parent CSV(HRF) [when they form over the Philippine Sea and Borneo (Figs. 14a–e)] to develop HRF cyclones/events in the three rainfall centers west of the South China Sea. In contrast, positive $\zeta_t(925 \text{ hPa})$ and $\zeta(925 \text{ hPa})$ centers spatially coincide with the CSV(HRF) centers for all four groups of CSV(HRF) formations east of the South China Sea (Figs. 14f–i). CSV(HRF) for these four groups can develop, but cannot propagate. The vorticity budget for the five groups of westward-propagating CSV(HRF) reveals the positive $\zeta_t(925 \text{ hPa})$ centers west of the $\zeta(925 \text{ hPa})$ centers of these vortices are primarily contributed by total vorticity advection, driven primarily by strong easterlies from the PHS-type cold surge flow. For those nonpropagating CSV(HRF), the stagnation of these vortices is attributed to vortex stretching by the low-level convergence of these CSV(HRF). To save space, $\zeta_t(925 \text{ hPa})$ contributed by both vorticity advection and vortex stretching for both westward-propagating and stagnant in situ CSV(HRF) are posted online (http://eamex.iastate.edu/publication/vorticity_budget_181HRF.pdf).

7. Concluding remarks

Cheang (1977) suggested the peninsular Malaysia HRF event is formed by the interaction of easterly waves with the cold surge flow. Yokoi and Matsumoto (2008) showed the occurrence of the central Vietnam HRF event requires the presence of a cold surge flow. Recently, Chen et al. (2012b,c) demonstrated the formation of the central Vietnam HRF occurs when the three monsoon modes (30–60, 10–20, and 5 day) exhibit constructive in-phase interference, and also synchronizes with the occurrence of the northwestern Pacific explosive cyclone. The current study determined the development of CSV(HRF) and their corresponding HRF cyclones/events are more complex than previously understood. According to Fig. 1, there are seven heavy rainfall centers around the east and west coasts of the South China Sea. In total, 181 HRF events during the 1979–2012 period were identified by DFO over these rainfall centers. Backtracking these HRF events along their trajectories to the formation location of their parent CSV(HRF), three important aspects about the development mechanisms of both CSV(HRF) and HRF cyclones/events are disclosed: 1) the formation mechanism of CSV(HRF), 2) propagation properties of CSV(HRF), and 3) the development mechanism of HRF cyclones/events. Because of the research scope for this study, our findings are reported in two parts—the first two aspects found herein are summarized below, while the third aspect will be reported in Part II.

The new findings regarding the formation mechanism and propagation properties are summarized here.

a. Formation mechanism of CSV(HRF)

1) PREFERRED TYPE OF COLD SURGE FLOW

Two CSV(HRF) formation mechanisms are identified through Figs. 4, 6, and 7, and summarized in Tables 3 and 4:

- Philippine CSV(HRF) are formed by the interactions of easterly waves with the PHS-type cold surge flow and the surface island-chain trough.
- Borneo CSV(HRF) are generated by the interactions of the SCS-type cold surge flow with Borneo orography and cyclonic shear flow around the near-equator trough.

2) GEOGRAPHIC PREFERENCE

Synoptically, the formation of Philippine and Borneo CSV(HRF) requires the surface island-chain trough and the near-equator trough, respectively. The former trough appears east of the Philippines, across Taiwan to southern Japan, while the latter trough exists across Borneo. Thus, these two troughs facilitate the formation of these two groups of CSV(HRF) in the vicinity of the Philippines and Borneo, respectively, as summarized in Fig. 8.

3) PREFERRED FORMATION TIME OF DAY

A great majority (~78%) of the Philippine CSV(HRF) forms at 0600 UTC, whereas the Borneo CSV(HRF) form during a window between 2100 and 0000 UTC. These observations are summarized in Fig. 9. The former CSV(HRF) form when the minimum semidiurnal p_s component propagates across the Philippines to trigger deep convection in the afternoon. In contrast, the latter CSV(HRF) form when the morning cold downslope flow of Borneo collides with the SCS-type cold surge flow—the Houze et al. (1981) mechanism.

b. Propagation properties of CSV(HRF)

Indicated by trajectories between HRF events and their parent CSV(HRF) in Figs. 2a–c, both Philippine and Borneo CSV(HRF) can propagate westward across the South China Sea and develop into HRF events in the three rainfall centers (central Vietnam, peninsular Malaysia, and southeastern Sumatra) west of the South China Sea. In contrast, some of these two groups of CSV(HRF) in Figs. 2d and 2e become stagnated over the four rainfall centers (northern and southern Philippines, Borneo, and Java) east and south of the South China Sea. These two propagation properties are shown in Figs. 11 and 12. The vorticity budget analysis shows the PHS-type (SCS type) of cold surge flow facilitates

(hinders) the westward propagation of CSV(HRF) across the South China Sea (Figs. 13 and 14).

Without comparing the CSV(HRF) formation and propagation activity over the countries around the South China Sea, it is difficult, if not impossible, to find these crucial factors determining the formation and propagation mechanisms of CSV(HRF). This approach provides a more in-depth perspective for these mechanisms, but new findings also lead us to raise the following issues for future research efforts:

- 1) The geographic preference for CSV(HRF) formation is affected by locations of both the island-chain surface and the near-equator troughs. How does the climatology of these two troughs affect the daily synoptic development of these two troughs? What roles do these two troughs play in the winter monsoon circulation? How does the ENSO cycle affect the activity of HRF events through these two troughs?
- 2) The diurnal variation of atmospheric circulation/weather systems has not been well simulated or forecasted by either regional or global models for climate and weather forecasts around the South China Sea (e.g., Gianotti et al. 2012). This possible model bias may need a serious effort to improve the modeling for both diurnal and semidiurnal modes.
- 3) The nighttime radiative cooling and convective/stratiform rainfall (Wu et al. 2008) over the central Borneo mountains have not been well explored. Accurate forecasts of the Borneo CSV(HRF) formation need some effort to explore the orography cooling and convection over Borneo.
- 4) The flow types of cold surge within the South China Sea primarily determine the formation mechanism of the Philippine and Borneo CSV(HRF), and their propagation properties. These flow types are primarily determined by the midlatitudes–tropic interaction, but the performance of operational models for the winter monsoon, particularly this interaction, has not attracted much research attention.

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