Development and Formation Mechanism of the Southeast Asian Winter Heavy Rainfall Events around the South China Sea. Part II: Multiple Interactions*

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ABSTRACT

About 44% of the cold-season heavy rainfall/flood (HRF) events around the South China Sea require six days or longer to develop from the formation time of their parent cold surge vortices (CSVs). Formations for both the parent CSV and HRF event are involved with interactions of the concerned vortices with two different cold surge flows. The occurrence frequency of the East Asian cold surge flow varies from 4.5 to 6 days. The longevous CSVs enable their developments to interact with the second cold surge flows between formations of these CSVs and HRF events. Two requirements for the formation of HRF events are 1) synchronized occurrence of the HRF event and the northwestern Pacific explosive cyclone and 2) simultaneous occurrence of the maximum speeds among westerlies of the northwestern Pacific explosive cyclone and easterlies of the tropical trade winds and the HRF event. These requirements cannot be met by the CSV at its second maximum peak intensity, but the CSV at this stage plays an indispensable role for the formation of the HRF event to make its intensity and rainfall amount larger than those HRF events without this relay intensification. The development of an HRF event through multiple interactions of CSVs with sequential cold surge flows may pose difficulties to numerically simulate/predict the occurrence of these HRF events over the cold-season rainfall centers around the South China Sea.

1. Introduction

An effort is made in this study to explore three development aspects of cold surge vortices (CSVs) into heavy rainfall flood (HRF) events over the winter rainfall centers around the South China Sea (SCS): 1) CSV(HRF) formation mechanism [CSV(HRF) indicates a CSV that develops into an HRF cyclone and/or noncyclone event (cyclone/event)], 2) CSV(HRF) propagation properties, and 3) development processes of HRF cyclones/events.

New findings for the aforementioned aspects in this study include the following:

- 1) CSV(HRF) only form in the Philippine vicinity and Borneo by different mechanisms. The former (latter) CSV(HRF) also exhibits a formation time preference at 0600 UTC (0000 UTC) and an interaction preference with the Philippine Sea (South China Sea)—type cold surge flow within the South China Sea.
- 2) Seven rainfall centers around the South China Sea are established by HRF events from the Philippine vicinity and Borneo CSV(HRF). Propagation properties for CSV(HRF) across the South China Sea are determined by the flow type of cold surge in this sea.
- 3) The development of CSV(HRF) into HRF cyclones/events is accomplished through the multi-interaction of CSV(HRF) with sequential cold surge flows intruding into the South China Sea and impacting the North Pacific synoptic systems.

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TABLE 1. Averaged propagation properties of CSV(HRF) across the South China Sea. The life cycle of CSV(HRF) are separated into two groups: boldface for life cycle $\sim >6$ days and italic for life cycle <6 days. Numbers in parentheses following all averaged values shown in columns 4–6 are standard deviations.

Item	Formation location of CSV	Location of HRF event	Traveling time/life cycle of CSV(HRF)	Propagation speed	Distance between locations of CSV(HRF) formation and HRF event occurrences
West of the SCS	Philippine vicinity	<i>Central Vietnam</i>	4.5 (1.2) days	3.7° (3.5°) day ⁻¹	16.8° (4.2°)
		Malaysia	7.3 (1.2) days	3.2° (2.8°) day⁻¹	23.4° (3.4°)
		Sumatra	7.5 (1.3) days	3.6° (2.9°) day⁻¹	26.8° (3.8°)
	Borneo	Malaysia	7.1 (1.2) days	1.6° (1.4°) day⁻¹	11.2° (1.7°)
		Sumatra	6.0 (1.0) days	1.3° (0.8°) day⁻¹	7.6° (0.8°)
East of the SCS	Philippine vicinity	<i>Northern Philippines</i>	2.0 (0.8) days	4.6° (3.2°) day ⁻¹	9.1° (2.6°)
		<i>Southern Philippines</i>	2.0 (0.8) days	4.6° (3.5°) day ⁻¹	9.1° (2.8°)
	Borneo	Borneo	5.8 (1.5) days	0° (0.3°) day⁻¹	0° (0.5°)
		Java	5.8 (1.2) days	0° (0.2°) day⁻¹	0° (0.2°)

The first two aspects of CSV(HRF) development processes were reported in (Chen et al. 2015, hereafter Part I) while the third aspect is the focus of this paper.

Prior to the Winter Monsoon Experiment (WMONEX; Greenfield and Krishnamurti 1979), Cheang (1977) suggested that the peninsular Malaysia HRF event develops from the western tropical Pacific easterly vortex. Following this suggestion, Yokoi and Matsumoto (2008) found that the required synoptic condition is the presence of cold surge flow for the development of HRF cyclones/events in central Vietnam. Later, Chen et al. (2012a,b) showed the HRF cyclone/event occurs when three monsoon modes (30–60, 12–24, and 5 day) exhibit a constructive, in-phase interference and synchronizes with the occurrence of a western Pacific explosive cyclone (Sanders and Gyakum 1980). In Part I, it was found the HRF cyclones/events developed only from CSV(HRF) formed in the Philippine vicinity and Borneo (Figs. 2 and 8 of Part I), instead of the western tropical Pacific easterly vortices. Observed by previous studies (Chen et al. 2012a,b, 2013a,b), the development of an HRF event from its parent CSV(HRF) involves interactions twice with cold surge flows: formations from this CSV(HRF) and the corresponding HRF event. In fact, an additional interaction of this CSV(HRF) with a cold surge flow may occur between the formations of the parent CSV(HRF) and the HRF event if this development has a life cycle ≥ 6 days.

As observed in Part I and summarized in Table 1, the average development time for each group of CSV(HRF) (i.e., the time for these vortices to travel across the South China Sea or become stagnated east of this sea) varies on average from two to more than seven days, so their propagation speeds and distances differ greatly from each other. As inferred in Part I, the occurrence of HRF cyclones/events is likely caused by the multi-interaction of the parent CSV(HRF) with sequential cold surge flows intruding on the South China Sea and the impact of some

North Pacific synoptic systems. Thus, the primary issue addressed herein is how the CSV(HRF) develops into HRF cyclones/events through the multi-interaction of CSV(HRF) with different cold surge flows and the impact of the Pacific synoptic systems. This development process is reflected by the CSV(HRF) intensification and rainfall enhancement, which will be illustrated through a dynamic–hydrologic–thermodynamic process. This process will be elucidated by the budget analyses of vorticity, water vapor, and velocity potential, and special characteristics of certain synoptic elements in the North Pacific basin.

To pursue the goal described previously, this study is organized in the following manner. Data from Part I are also used herein; the details can be found in Part I. The possible multi-interaction to develop the CSV(HRF) into an HRF event is identified in section 2 through the chronicled development of maximum vorticity for nine CSV(HRF) groups. The interrelationships among the three budget analyses in intensifying the CSV(HRF) and maintaining the HRF event are also presented in this section. Two typical case studies for the synoptic development of CSV(HRF) into HRF cyclones/events through triple maximum intensities of CSV(HRF) with cold surge flows are illustrated as examples in section 3. Because there were 181 HRF events identified by the Dartmouth Flood Observatory (DFO; DFO 2013), a statistical analysis is conducted in section 4 to substantiate the CSV(HRF) development processes into HRF cyclones/events revealed from case studies in the previous section. Formation of HRF events in central Vietnam and Malaysia needs to satisfy two requirements: 1) synchronized occurrence of the HRF event and North Pacific explosive cyclone (Sanders and Gyakum 1980) and 2) simultaneous occurrence of maximum speeds between explosive cyclone westerlies and the easterlies of tropical trade winds and HRF cyclones/events (Chen et al. 2012a, 2013a). These two requirements are met by a great

majority of all DFO HRF events, but not by the second maximum intensification of CSV(HRF) to form HRF events through the triple maximum intensification. Thus, the role played by the second maximum intensification of CSV(HRF) is assessed as a relay development of HRF cyclones/events in [section 5](#). Concluding remarks of the study herein and suggestions for future efforts to explore dynamic and physical processes involved with the formation of CSV(HRF) and HRF events, and the forecast improvements of HRF events, are offered in [section 6](#).

2. Identification of multi-interaction CSV(HRF) and development diagnosis

a. Identification of multi-interaction CSV(HRF)

The occurrence frequency of the East Asian cold surge may vary from 4.5 days during the warm ENSO phase to 6 days during the cold ENSO phase (e.g., [Chen et al. 2004](#)). If the averaged traveling time/life cycle of CSV(HRF) in some groups ([Table 1](#)) is over 4.5 days, some CSV(HRF) in these groups may have a traveling time longer than 4.5 days by considering their standard deviation time. The development of HRF cyclones/events from these longevous parent CSV(HRF) may be achieved through multi-interactions with sequential cold surge flows. To confirm this interference, a procedure to identify this multi-interaction is developed:

- (i) The CSV(HRF) vorticity averaged over the area with a threshold value $\geq 1.8 \times 10^{-5} \text{ s}^{-1}$ is used as an indicator of the CSV(HRF) intensity. Following the Lagrangian approach along a CSV(HRF) trajectory, the time series for this area-averaged CSV(HRF) vorticity ζ^o is prepared.
- (ii) Following [von Storch and Zwiers \(2002\)](#), the linear trend of a CSV(HRF) ζ^o time series over its life cycle is removed. The maximum ζ^o exceeding one standard deviation (σ^{ζ^o}) of the detrended ζ^o time series is used to identify the maximum intensities of CSV(HRF) over their life cycles.
- (iii) The identified maximum intensities of a CSV(HRF) over its life cycle are checked to see whether these maximum intensities are caused by this CSV(HRF) interactions with sequential cold surge flows whose types are determined by the procedure presented in [Part I](#).
- (iv) If the formation/occurrence of an HRF event that accompanies CSV(HRF) maximum intensity coincides with the occurrence of a northwestern Pacific explosive cycle, one should check whether this CSV(HRF) maximum intensity is caused by the interaction of a new cold surge or maintained by an aging surge. The impact by the two requirements pointed

out previously in the formation/occurrence of an HRF event can be found in [Chen et al. \(2012b\)](#).

Following the four-step procedure described above, the time taken by a CSV(HRF) from its formation to the occurrence location of an HRF event is shown in [Fig. 1](#). HRF cyclones/events develop from their parent CSV(HRF) and may exhibit the maximum ζ^o at 925 hPa [$\zeta^o(925 \text{ hPa})$] intensity twice or three times. The HRF event occurs by the impact of the two requirements, in addition to the interaction of either a new or an aging cold surge. For convenience, HRF events are designated by HRF_m^n , where n represents the number of the maximum intensities their parent CSV(HRF_m^n) undergoes and m denotes the number of cold surge flows with which these CSV(HRF_m^n) interact. As indicated by the vertical yellow stripe in [Fig. 1](#), HRF_2^3 and HRF_3^3 events form if the life cycles of their parent CSV(HRF_2^2) and CSV(HRF_3^3) [$\text{CSV}(\text{HRF}_1^1)$ and $\text{CSV}(\text{HRF}_2^2)$] are ≥ 6 days (≤ 6 days). Interesting features of [Fig. 1](#) are highlighted below.

1) WEST OF THE SOUTH CHINA SEA

- Over central Vietnam, the population of HRF events consists of only 22% of HRF_2^3 events, but 78% of HRF_2^2 events. In contrast, the great majority of the HRF population in peninsular Malaysia are $\text{HRF}_2^3 + \text{HRF}_3^3$ events developed from the Philippine CSV(HRF_m^3) (78%) and $\text{HRF}_2^2 + \text{HRF}_3^3$ events developed from the Borneo CSV(HRF_m^3) (94%).
- As observed in [Part I](#), the Philippine (Borneo) CSV(HRF) forms with the Philippine Sea (PHS)-type (SCS type) cold surge flow. In central Vietnam, the HRF_2^2 events form in the second maximum intensities of their parent CSV(HRF_2^2) are interacted with 13 PHS-type and 16 SCS-type cold surge flows. For the formation of HRF_2^3 events, the second maximum intensities of their parent CSV(HRF_2^3) interacting with 4 PHS- and 4 SCS-type cold surge flows, respectively, but these vortices are maintained by these two types of cold surge flow until they are strengthened by the impact of two requirements for the formation of the HRF_2^3 event.

2) EAST OF THE SOUTH CHINA SEA

- Over the Philippines, both the northern and southern Philippine HRF_1^2 events develop directly from their parent Philippine CSV(HRF_1^2) through their interactions with only one PHS-type cold surge flow.
- For Borneo and Java, the HRF event population includes approximately 45% of HRF_2^2 events, approximately 52% of HRF_2^3 events, and approximately 3% of HRF_3^3 event. These events develop through their

FIG. 1. The life cycle/time taken by a CSV(HRF_m^n) to develop from its formation location to reach the formation location of the HRF_m^n event in seven rainfall centers. Traveling time is projected on the abscissa and the case number of HRF_m^n events is scaled on the ordinate. All (181) HRF_m^n events are classified into four groups, HRF_3^3 , HRF_2^3 , HRF_2^2 , and HRF_1^2 , and are denoted by a solid triangle, open triangle with a dot inside, open circle with a dot inside, and a short line with a dot located at the center, respectively. The second maximum intensity of CSV(HRF_m^n) is denoted by an open circle. The red (blue) symbol indicates the CSV(HRF_m^n) interaction with the SCS-type (PHS type) cold surge flow. Dates of the second maximum intensity of CSV(HRF_m^n) and occurrence of HRF_2^2 in each rainfall center are linked by a thin blue and a thin red line, respectively. The vertical green and yellow stripes stratify the times needed to develop the second peak intensity of CSV(HRF_m^n), and to form HRF_2^2 , HRF_2^3 , and HRF_3^3 events. (A schematic diagram in Fig. 9 further illustrates this time stratification for the occurrence of these four different events.)

interactions only with two sequential SCS-type cold surge flows, except the HRF_3^3 event develops through its interactions with three sequential SCS-type cold surge flows.

b. Diagnostic budget analysis

Our major concern in this study is how a CSV(HRF_m^n) intensifies and develops into a HRF_m^n cyclone/event through the multi-interaction of CSV(HRF_m^n) with the

intrusion of East Asian cold surge flow into the South China Sea. This interaction takes place by a collision between the cold dry midlatitude air mass and the warm moist tropical perturbation in the South China Sea. Thus, a heavy rainfall event developed by the intensified cyclone system should be achieved by this midlatitude–tropic interaction through the dynamic–hydrologic–thermodynamic process. The following budget analyses will be performed to illustrate this interaction.

1) VORTICITY BUDGET

The strength of a vortex is often measured by the vorticity ζ over an area. Thus, the CSV(HRF) intensification may be illustrated by the vorticity tendency ζ_t contributed by two dynamic processes—vorticity advection ζ_t^A and vortex stretching ζ_t^V :

$$\zeta_t = \underbrace{-\mathbf{V} \cdot \nabla(\zeta + f)}_{\zeta_t^A} - \underbrace{(\zeta + f)\nabla \cdot \mathbf{V}}_{\zeta_t^V}, \quad (1)$$

where $f = 2\Omega \sin\phi$ and Ω , and ϕ are Earth's rotation rate and latitude, respectively, and $\mathbf{V}$ is the wind vector. The vorticity of CSV(HRF) can be distributed by ζ_t^A , but is generated by convergence of the air mass flux through ζ_t^V .

2) WATER VAPOR BUDGET

Rainfall is primarily maintained by the convergence of the water vapor flux. Thus, the water vapor budget may be approximated by

$$P \sim -\nabla \cdot \mathbf{Q}. \quad (2)$$

The water vapor flux $\mathbf{Q}$ can be separated into rotational $\mathbf{Q}_R$ and divergent $\mathbf{Q}_D$ components,

$$\mathbf{Q} = \mathbf{Q}_R + \mathbf{Q}_D,$$

where $\mathbf{Q}_D$ can be measured by gradients of the potential function $\chi_{\mathbf{Q}}$ of water vapor flux (Chen 1985), that is, $\mathbf{Q}_D = \nabla\chi_{\mathbf{Q}}$. Thus, Eq. (2) may be written as

$$P \sim -\nabla \cdot \mathbf{Q}_D = -\nabla^2 \chi_{\mathbf{Q}}. \quad (3)$$

Because water vapor is scalar, $\mathbf{Q}_D$ should be driven by the divergent flow, and $-\nabla \cdot \mathbf{Q}_D$ is intensified by the convergence of air mass flux, $-\nabla \cdot \mathbf{V}$, to enhance/maintain rainfall of a CSV(HRF) through Eqs. (2) and (3). The spatial structure of $\chi_{\mathbf{Q}}$ should resemble that for the χ velocity potential.

3) THE χ MAINTENANCE EQUATION

The divergent circulation portrayed by velocity potential χ is often expressed by the convergence or divergence of air mass flux. The response of the atmospheric circulation to thermodynamic processes, sensible heating advection, and diabatic heating is the development of divergent circulation. Combining the continuity and thermodynamic equations, one can obtain the χ maintenance equation (Chen and Yen 1991a,b),

$$\chi = \underbrace{\nabla^{-2} \left\{ -\frac{\partial}{\partial p} \left[\frac{1}{\sigma} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) \right] \right\}}_{\chi_H} + \underbrace{\nabla^{-2} \left[\frac{\partial}{\partial p} \left(\frac{1}{c_p \sigma} \dot{Q} \right) \right]}_{\chi_{\dot{Q}}}, \quad (4)$$

where σ , T , c_p , $\dot{Q}$, and p are static stability, temperature, specific heat at constant pressure, diabatic heating, and pressure, respectively. The thermal tendency $\partial T/\partial t$ is usually not a significant thermal term. Thus, velocity potential is primarily maintained by the vertical differentiations of heat advection and diabatic heating:

$$\nabla \cdot \mathbf{V} = \nabla^2 \chi \simeq \nabla^2 \chi_H + \nabla^2 \chi_{\dot{Q}}. \quad (5)$$

Note that the latent heat released by condensation is a major contribution to $\dot{Q}$ (Yanai et al. 1973), so the direct atmospheric response to this heating is the development of divergent circulation. If $\chi_H \ll \chi_{\dot{Q}}$ and $\nabla^2 \chi_H \ll \nabla^2 \chi_{\dot{Q}}$, the divergent circulation will be strengthened by the latent heat released from cumulus convection/rainfall,

$$\chi \sim \nabla^{-2} \left[\frac{\partial}{\partial p} \left(\frac{1}{c_p \sigma} \dot{Q} \right) \right] \sim \chi_{\dot{Q}} \quad \text{and} \quad -\nabla \cdot \mathbf{V} \sim -\nabla^2 \chi_{\dot{Q}}. \quad (6)$$

4) THE DYNAMIC-HYDROLOGIC-THERMODYNAMIC PROCESS TO INTENSIFY CSV(HRF_mⁿ)

The enhancement of air mass flux convergence would lead to the intensification of a CSV(HRF_mⁿ) through vortex stretching in Eq. (1). The intensification of a CSV(HRF_mⁿ) through the multi-interaction of sequential cold surge flows can be illustrated through the inter-relationship among Eqs. (1), (3), and (6). The inter-relationships among the dynamical, hydrological, and thermodynamical processes to intensify CSV(HRF) may be illustrated by the following contrasts: $-\nabla \cdot \mathbf{V}$ versus $-\nabla \cdot \mathbf{Q}$, $-\nabla \cdot \mathbf{Q}$ versus precipitation (P), and $-\nabla \cdot \mathbf{V}_{\dot{Q}}$ versus $-\nabla \cdot \mathbf{V}$, shown in Fig. 2.

3. Case analysis for the development of HRF cyclone/events through multi-interactions

Despite previous efforts (Cheang 1977; Yokoi and Matsumoto 2008; Chen et al. 2012a,b, 2013a,b), the

FIG. 2. Schematic diagram to illustrate the relationship between ζ_t^V vs $-\nabla \cdot \mathbf{V}$, $-\nabla \cdot \mathbf{V}$ vs $-\nabla \cdot \mathbf{Q}$, $-\nabla \cdot \mathbf{Q}$ vs P , and $-\nabla \cdot \mathbf{V}_Q$ vs $-\nabla \cdot \mathbf{V}$.

CSV(HRF) formation and development into HRF events through the multi-interaction of CSV(HRF) with sequential cold surge flows was not noticed. To avoid redundancy, the synoptic developments of a typical case east and another typical case west of the South China Sea are presented. The budget analyses for vorticity, water vapor, and velocity potential formulated in section 2 are performed to illustrate the CSV(HRF_mⁿ)–HRF_mⁿ development processes for one HRF₂³ event of these two cases. A great majority of HRF_mⁿ cyclones/events in peninsular Malaysia (PM) develop from the Philippine CSV(HRF_mⁿ) through the multi-interactions with the PHS-type cold surge flows. Thus, a typical Philippine CSV(HRF₂³)–HRF₂³(PM) case is selected to illustrate the development of an HRF₂³ event west of the South China Sea. Over one-half of the HRF_mⁿ in Borneo (BO) cyclones/events evolve from the Borneo CSV(HRF_mⁿ) through multi-interactions with the SCS-type cold surge flow. A typical Borneo CSV(HRF₂³)–HRF₂³(BO) case is chosen to depict how a HRF₂³(BO) event develops east of the South China Sea. Four cases of CSV(HRF₃³)–HRF₃³ are identified (Fig. 1). [To save space, the developments of a Philippine CSV(HRF₃³)–HRF₃³(PM) case and Borneo CSV(HRF₃³)–HRF₃³(BO) case are shown in the supplemental material.] Because nine groups of HRF_mⁿ events are categorized, the synoptic development and vorticity budget analysis for a typical case of the remaining seven groups, perhaps through either single, double, or triple interactions with sequential cold surge flows, are posted online (http://eamex.iastate.edu/publication/SEAsia_HRF_partII_supp.pdf).

a. Case 1: Development of a Malaysia HRF₂³ event from its parent Philippine CSV(HRF₂³)

1) VORTICITY TIME SERIES

Following the evolution from its formation time at 0600 UTC 4 November 2010 (Fig. 3b) into a peninsular

Malaysia HRF₂³ event at 1200 UTC 9 November 2010 (Fig. 3d), the time series of ζ^o (925 hPa) for CSV(HRF₂³) is shown in Fig. 3a. Attached to this time series is the time series for the 925-hPa wind vector [$\mathbf{V}$ (925 hPa)] at the maximum isotach location of the related northeastern Asia cold surge (indicated in Figs. 3b–d). Using the identification procedure in section 2a, three ζ^o (925 hPa) maxima emerge at 0600 UTC 4 November 2010, 0600 UTC 7 November 2010, and 1200 UTC 9 November 2010. Shown by the $\mathbf{V}$ (925 hPa) time series on the top of Fig. 3a, the three ζ^o (925 hPa) maxima are responses for this CSV(HRF₂³) interactions with the sequential intrusions of the two cold surge flows (indicated by red vectors) and the strengthened basin-scale circulation related to the northwestern Pacific explosive cyclone. The development of the HRF₂³(PM) cyclone/event is reflected by the increasing intensification of these three ζ^o (925 hPa) maxima from $2.3 \times 10^{-5} \text{ s}^{-1}$ (first maximum) to $3.1 \times 10^{-5} \text{ s}^{-1}$ (third maximum) through the following processes: 1) a linear increasing trend of the CSV(HRF₂³) diurnal variation of its vorticity across the South China Sea, 2) the responses from the CSV(HRF₂³) interaction with the sequential intrusions of the two cold surge flows marked by red vectors on the $\mathbf{V}$ (925 hPa) time series, and 3) the intensified tropical trades coupled with the occurrence of the northwestern Pacific explosive cyclone. The multi-interactions of CSV(HRF₂³) with cold surge flows and the tropical trade easterlies are further illustrated by the 925-hPa streamline charts (Figs. 3b,c), when the CSV(HRF₂³) reaches its three ζ^o (925 hPa) maxima in Fig. 3a.

2) VORTICITY BUDGET ANALYSIS

Inferred from the ζ^o (925 hPa) time series and the 925-hPa streamline charts (Fig. 3), the development of the HRF₂³(PM) cyclone/event through the multi-interaction of a CSV(HRF₂³) with sequential cold surge flows can be substantiated by the vorticity budget analysis of Eq. (1). Because of the interaction of a Philippine CSV(HRF₂³) with the PHS-type cold surge flow, the strong easterlies for this cold surge flow allows this CSV(HRF₂³) to propagate westward, as indicated by ζ_t^A . The intensification of this CSV(HRF₂³) may be also enhanced by the horizontal convergence of air mass flux through vortex stretching. According to Eq. (1), vorticity can be obtained by integrating this equation through a central finite difference approach:

$$\zeta^C(t + \Delta t) = \zeta^C(t - \Delta t) + \int_{t-\Delta t}^{t+\Delta t} \zeta_t^o(t) 2 dt. \quad (7)$$

Using Eq. (7), the time series for ζ^C (925 hPa) and ζ^o (925 hPa) averaged over this CSV(HRF₂³) domain with

FIG. 3. Synoptic development of a Philippine CSV(HRF₃) from its formation at 0600 UTC 4 Nov 2010 into a peninsular Malaysia HRF₂ event at 1200 UTC 9 Nov 2010. (a) Time series for $\zeta^\circ(925\text{ hPa})$, which is $\zeta(925\text{ hPa})$ averaged over the area of the Philippine CSV(HRF₃) with $\zeta(925\text{ hPa}) \geq 1.8 \times 10^{-5}\text{ s}^{-1}$. This $\zeta^\circ(925\text{ hPa})$ time series is prepared with the Lagrangian approach following this CSV(HRF₃) trajectory. The $\zeta^\circ(925\text{ hPa})$ trend (thin red line) generated by a least squares fit approach is superimposed on the $\zeta^\circ(925\text{ hPa})$ time series. One std dev (wide yellow stripe) is added on the $\zeta^\circ(925\text{ hPa})$ trend. The time series for $V(925\text{ hPa})$, with the maximum isotach associated with the northeastern Asia cold surge juxtaposed with a surface high and low or the maximum isotach over Bohai and the Yellow Sea, is shown at the top of (a). (b)–(d) The maximum cold surges at the three (maximum) peak intensities of the Philippine CSV(HRF₃) are marked by thick red arrows on the $V(925\text{ hPa})$ time series and also on the 925-hPa streamline charts with thick blue arrows. As indicated by the $\zeta^\circ(925\text{ hPa})$ time series, CSV(HRF₃) reaches its three maximum intensities, indicated by $\zeta^\circ(925\text{ hPa}) \geq 1$ std dev in the $\zeta^\circ(925\text{ hPa})$ time series. The 925-hPa streamline charts superimposed with P at these three special times are also shown. During the CSV(HRF₃) formation at 0600 UTC 4 Nov 2010, the island-chain trough, the easterly wave, the CSV(HRF₃) formation location, and the trajectory of CSV(HRF₃) are marked in (b) by a solid purple line, red line, red cross, and red dashed lines, respectively. The location where CSV(HRF₃) reaches its second maximum intensity is marked by a red cross in (c). Red crosses mark the locations for the Malaysia HRF₂ event and the northwestern Pacific explosive cyclone in (d). The latter is also denoted by a boldface red letter L.

$\zeta(925\text{ hPa}) \geq 1.8 \times 10^{-5}\text{ s}^{-1}$ are shown in Fig. 4a; ratios for $\bar{\zeta}^C(925\text{ hPa})/\bar{\zeta}^\circ(925\text{ hPa})$ and $\text{RMS}[\zeta^C(925\text{ hPa})]/[\zeta^\circ(925\text{ hPa})]$ are 98% and 99%, respectively, where the overbar and RMS denote the time mean and root-mean-square of the values, respectively. Additionally, the correlation coefficient $\sigma(\zeta^C, \zeta^\circ) = 0.95$. These statistics strongly indicate that the intensification of this

CSV(HRF₃) is well determined by both $\zeta_t^A(925\text{ hPa})$ and $\zeta_t^V(925\text{ hPa})$ processes.

The time series for $\zeta_t^\circ(925\text{ hPa})$, $\zeta_t^A(925\text{ hPa})$, and $\zeta_t^V(925\text{ hPa})$ averaged over this CSV(HRF₃) domain $\zeta(925\text{ hPa}) \geq 1.8 \times 10^{-5}\text{ s}^{-1}$ are also shown in Fig. 4a. Ratios of $\text{RMS}[\zeta_t^A(925\text{ hPa})]/\text{RMS}[\zeta_t^\circ(925\text{ hPa})]$ and $\text{RMS}[\zeta_t^V(925\text{ hPa})]/\text{RMS}[\zeta_t^\circ(925\text{ hPa})]$ are 54% and

FIG. 4. The vorticity budget analysis for the Philippine CSV (HRF₂³), when it reaches the second maximum intensity at 0000 UTC 7 Nov 2010 (Fig. 3). (a) Time series for V and ζ^o at 925 hPa in Fig. 3a are added with time series for ζ_t^c , ζ_t^A , and ζ_t^V at 925 hPa. The 925-hPa streamline charts are superimposed with (b) ζ_t , (c) ζ_t^A , and (d) ζ_t^V at 925 hPa. The open red circle is the area of CSV (HRF₂³) with $\zeta(925 \text{ hPa}) \geq 1.8 \times 10^{-5} \text{ s}^{-1}$ and the CSV (HRF₂³) center is indicated by a red cross.

46%, respectively. Correlation coefficients $\sigma[\zeta_t^A(925 \text{ hPa}), \zeta_t^o(925 \text{ hPa})]$, and $\sigma[\zeta_t^V(925 \text{ hPa}), \zeta_t^o(925 \text{ hPa})]$ are 0.87 and 0.79, respectively. Judging by the time series for $\zeta_t^o(925 \text{ hPa})$, $\zeta_t^A(925 \text{ hPa})$, and $\zeta_t^V(925 \text{ hPa})$, the intensification of this CSV (HRF₂³) over its life cycle is essentially attributed to the aggregative effects of both $\zeta_t^A(925 \text{ hPa})$ and $\zeta_t^V(925 \text{ hPa})$ processes.

Note that $\zeta_t^o(925 \text{ hPa})$ reaches its three specially amplified maxima 6 h prior to the three $\zeta_t^o(925 \text{ hPa})$ maximum. For this reason, we select 0000 UTC 7 November 2010 [6 h before $\zeta_t^o(925 \text{ hPa})$ reaches its second maximum

in Fig. 3a] to illustrate the relay intensification for this Philippine CSV (HRF₂³) by dynamic processes included in the vorticity equation, Eq. (1). Horizontal distributions for $\zeta_t(925 \text{ hPa})$, $\zeta_t^A(925 \text{ hPa})$, and $\zeta_t^V(925 \text{ hPa})$ are shown in Figs. 4b–d and are characterized by the following features:

- (i) Divided across the center of this CSV (HRF₂³) (Fig. 4c), the positive and negative values for $\zeta_t^A(925 \text{ hPa})$ are located over the western and southeastern part of this vortex, respectively. This

spatial structure of ζ_t^A (925 hPa) facilitates the westward propagation of this CSV(HRF₂³).

- (ii) The spatial relationship between ζ_t^V and the CSV(HRF₂³) is similar to that between ζ_t^A and this vortex. The interaction of this vortex with the cold surge flow through the convergence of air mass flux and vortex stretching strengthens the ζ_t^A effect.
- (iii) The close variations of ζ_t^o (925 hPa) and ζ_t^C (925 hPa) in Fig. 4a indicate the second ζ_t^o (925 hPa) maximum is developed constructively by a combination of ζ_t^A (925 hPa) and ζ_t^V (925 hPa).

Time variations of the Philippine CSV(HRF₂³) vorticity budget over its life cycle (Fig. 4a) and horizontal charts for this budget at 0000 UTC 7 November 2010, 6 h before this vortex reaches its second maximum intensity (Figs. 4b–d), indicate that both ζ_t^A and ζ_t^V contribute aggregatively to developing this CSV(HRF₂³) into a peninsular Malaysia HRF₂³ cyclone/event. This CSV(HRF₂³) intensification by the second cold surge flow in the middle of the South China Sea is a relay interaction to maintain/allow this vortex to continuously interact with this second cold surge flow. Eventually, this CSV(HRF₂³) vortex also intensifies by the strengthened tropical trade easterlies into a peninsular Malaysia HRF cyclone/event.

3) ANALYSIS OF WATER VAPOR BUDGET AND χ MAINTENANCE EQUATION

It is revealed from Fig. 4d that the dynamic development process of the Philippine CSV(HRF₂³) relay interaction is accompanied by the convergence of the air mass flux, $-\nabla \cdot \mathbf{V}$ (Fig. 5d), which plays a dual role in developing this CSV(HRF₂³). First, this convergence of air mass flux intensifies the CSV(HRF₂³) through vortex stretching (Fig. 4d). Second, according to Fig. 2, the convergence of water vapor flux toward the CSV(HRF₂³) center follows the convergence of air mass flux. This inference is confirmed by the spatial coincidence between centers of $-\nabla \cdot \mathbf{Q}$ (Fig. 5b) and $-\nabla \cdot \mathbf{V}$ (Fig. 5d), and by the temporal coincidence between the time series for both convergence variables averaged over the area of $P \geq 46 \text{ mm day}^{-1}$, that is, $(-\nabla \cdot \mathbf{V})^o$ and $(-\nabla \cdot \mathbf{Q})^o$ (Fig. 5a).

The P^o and $(-\nabla \cdot \mathbf{Q})^o$ time series for the CSV(HRF₂³) (Fig. 5a) are temporally coincident, and the centers for these two variables (Fig. 5b) are spatially coincident, too. Apparently, the rainfall increase for the CSV(HRF₂³) by the second PHS-type surge flow is supplied by the enhanced convergence of water vapor flux, as indicated by Eq. (2). Illustrated by Yanai et al. (1973), an essential part of the apparent diabatic heating $\dot{Q}$ is contributed by the latent heat from condensation L released by convection/precipitation, that is,

$$\frac{1}{g} \int_{p_s}^p \dot{Q} dp \sim LP \sim -L\nabla \cdot \mathbf{Q}, \quad (8)$$

where p and p_s are pressures at a given level and surface, respectively.

Shown by Eq. (4), for the χ maintenance equation, χ is essentially contributed by χ_H and $\chi_{\dot{Q}}$. The contribution ratio by these two variables on the CSV(HRF₂³) domain ($P \geq 46 \text{ mm day}^{-1}$) is about 1:7. Thus, we may approximate Eq. (5) by

$$-\nabla \cdot \mathbf{V} (\equiv -\nabla^2 \chi) \sim -\nabla^2 \chi_{\dot{Q}}, \quad (9)$$

so the convergence of air mass flux (Fig. 5d) is related to the heat for condensation by convection/rainfall (Fig. 5c) over the CSV(HRF₂³) center. In addition to this spatial coincidence, the correlation coefficient between $(-\nabla \cdot \mathbf{Q})^o$ and $(-\nabla^2 \chi_{\dot{Q}})^o$ is 0.92.

b. Case 2: Development of a Borneo HRF₂³ event from its in situ parent CSV(HRF₂³)

1) TIME SERIES AND BUDGET ANALYSIS OF VORTICITY

The development of a Borneo HRF₂³ cyclone/event from its in situ parent CSV(HRF₂³) over its life cycle, 18–25 December 2011, is used as an example to illustrate how its development is affected by the multi-interaction of this vortex with the sequential cold surge flows and the intensified tropical trades linked to the occurrence of a northwestern Pacific explosive cyclone. The time series of ζ^o (925 hPa) for this Borneo CSV(HRF₂³) over its life cycle is shown in Fig. 6a. Although ζ^o (925 hPa) undergoes a distinct diurnal variation, three specially amplified ζ^o (925 hPa) maxima (>1 standard deviation from the linear trend) emerge at 0000 UTC 18 December 2011, 1200 UTC 22 December 2011, and 0000 UTC 25 November 2011. The contrast between wind vectors for the three East Asian cold surges and the three ζ^o (925 hPa) maxima indicates the chronic intensification of this Borneo CSV(HRF₂³) is through its multi-interactions with two sequential SCS-type cold surge flows and tropical trade easterlies. This assessment is further confirmed by the 925-hPa streamline charts for these three special times (Figs. 6b–d)—the connection between the north-eastern Asia cold surge wind vector (east of the southern Korean Peninsula) and the Borneo CSV(HRF₂³) by the East Asia–South China Sea cold surge flow. As revealed from the continuous increase of ζ^o (925 hPa) maximum values, the intensification trend for CSV(HRF₂³) is initiated from the Borneo CSV(HRF₂³) formation to the Borneo HRF₂³ event occurrence.

FIG. 5. As in Fig. 4, but for analyses of the water vapor budget and the χ maintenance equation for the CSV (HRF₃) at 0000 UTC 7 Nov 2010. (a) Time series for V (925 hPa)/ ζ^o (925 hPa) of Fig. 3a are added to the top of Fig. 3a. Presented below it are the time series of ζ^i and ζ^o at 925 hPa, the time series of $(-\nabla \cdot \mathbf{Q})^o$ and a histogram of P^o , and time series of $(-\nabla \cdot \mathbf{V})^o$ and $(-\nabla^2 \chi_Q)^o$ at 925 hPa. On the right of (a) are horizontal distributions of (b) χ_D , Q_D , and $-\nabla \cdot \mathbf{Q}$; (c) χ_Q and $\nabla \chi_Q$ at 925 hPa and P ; (d) χ , ∇_D , and $-\nabla \cdot \mathbf{V}$ at 925 hPa; and (e) ψ and ζ at 925 hPa.

Integrating ζ^o (925 hPa) in time with Eq. (7), the ζ^C (925 hPa) time series is comparable to the ζ^o (925 hPa) time series in Fig. 7a; ratios of ζ^C (925 hPa)/ ζ^o (925 hPa) and $\text{RMS}[\zeta^C$ (925 hPa)]/ $\text{RMS}[\zeta^o$ (925 hPa)] are 96% and 96%, respectively, and the correlation coefficient $\sigma[\zeta^C$ (925 hPa), ζ^o (925 hPa)] is 0.94. Apparently, the temporal variation for ζ^o (925 hPa) is primarily attributed to two dynamic processes— ζ_t^A (925 hPa) and ζ_t^V (925 hPa). Actually, the ratio $\text{RMS}[\zeta_t^A$ (925 hPa)]/ $[\zeta_t^V$ (925 hPa)] over the life cycle for this Borneo CSV (HRF₃) is about 50%. Thus, ζ_t^o (925 hPa) is contributed more by ζ_t^V (925 hPa). Note that the role played by the two dynamic processes ζ_t^A (925 hPa) and ζ_t^V (925 hPa) to intensify this Borneo CSV (HRF₃) is opposite that for the Philippine CSV (HRF₂).

Shown in Fig. 6a, the formation of the parent Borneo CSV (HRF₂) and the ensuing HRF₂ cyclone/event in the present case are accomplished by the first and second interactions of this CSV (HRF₂) with the SCS-type cold surge flow, respectively, and the maintenance of this CSV (HRF₂) until its final intensification by the tropical

trade easterlies. Let us focus on the role played by the second interaction with an SCS-type cold surge flow in developing this vortex through the horizontal distributions of the dynamic processes in the vorticity budget. Thus, 6 h before ζ^o (925 hPa) for this CSV (HRF₃) reaches its second maximum, the vorticity budget at 0600 UTC 22 December 2011 is selected to illustrate these processes in Figs. 7b–d. The centers for three different vorticity tendencies are coincident with this CSV (HRF₃). The in situ development for this Borneo CSV (HRF₃) is reflected by this spatial coincidence of these three centers. Different from case 1, the nonpropagation property for this Borneo CSV (HRF₃) is reflected by the fact there is no positive ζ_t (925 hPa) west of the vortex center, because ζ_t^A (925 hPa) does not show such a spatial structure to support the westward propagation of the CSV (HRF₃) (Chen et al. 2013a). On the other hand, the SCS-type cold surge flow intensifies the cyclonic shear flow around Borneo, which leads to the enhancement of the air mass flux convergence, and, in turn, the vortex stretching ζ_t^V . Consequently, the intensification of this CSV (HRF₃) is

FIG. 6. As in Fig. 3, but for a Borneo CSV (HRF_2^3) with a life cycle from 0000 UTC 18 Dec to 0000 UTC 25 Dec 2011.

largely achieved by vortex stretching. The smaller value of ζ_t^A (925 hPa), compared to ζ_t^V (925 hPa), is consistent with the nonpropagation property of the Borneo CSV (HRF_2^3) (Chen et al. 2013a).

In view of the intensification of the CSV (HRF_2^3) to become a Borneo HRF_2^3 event through the CSV (HRF_2^3) interactions with two sequential cold surge flows and the final intensification by the intensified tropical trade easterlies (Figs. 6a and 7a), the second interaction is a relay dynamic process in this HRF_2^3 development.

2) ANALYSES OF THE WATER VAPOR BUDGET AND χ MAINTENANCE EQUATION

Following the intensification of the Borneo cyclonic shear flow by the second interaction of the Borneo CSV (HRF_2^3) with the SCS-type cold surge flow on 22 December 2011, the convergence of the air mass flux toward Borneo (Fig. 8d) is enhanced (Fig. 8a). This air mass flux convergence strengthens not only the vortex stretching, but also the convergence of the water vapor

flux (shown by Fig. 2). The high correlation (with a coefficient of 0.86) between time series of $(-\mathbf{V} \cdot \mathbf{V})^\circ$ and $(-\mathbf{V} \cdot \mathbf{Q})^\circ$ shown in Fig. 8a confirms this relationship. According to Eqs. (4) and (5), the second rainfall maximum for this CSV (HRF_2^3) on 22 November 2011 (Fig. 8c) is maintained by the enhancement of this CSV (HRF_2^3) $-\mathbf{V} \cdot \mathbf{Q}$ (Fig. 8b). This observation is substantiated by the correlation coefficient of 0.91, and ratio of mean and RMS values between $(-\mathbf{V} \cdot \mathbf{Q})^\circ$ and P° the time series in Fig. 8a; 92% and 90%, respectively.

Apparently, the enhancement of air mass flux convergence is an atmospheric response around this CSV (HRF_2^3) (Fig. 8d) to the heat released by convection/rainfall [Eqs. (6) and (8)] occurring during the second maximum intensity of this CSV (HRF_2^3) (Fig. 8c), as indicated by the center coincidence of χ_ϕ and χ over this CSV (HRF_2^3) center, and a large correlation coefficient between time series of $-\mathbf{V} \cdot \mathbf{Q}$ and $-\nabla^2 \chi_\phi$. Obviously, the relay development for this Borneo CSV (HRF_2^3) by its second interaction with the SCS-type cold surge flow is an

FIG. 7. As in Fig. 4, but for a Borneo CSV(HRF₂³) shown in Fig. 6.

important step to develop this CSV(HRF₂³) into a Borneo HRF₂³ event.

4. Statistics for the HRF cyclone/event development through the multi-interaction process

Over their life cycles, synoptic/dynamic development processes of two typical HRF₂³ cyclones/events through multi-interactions of their parent CSV(HRF₂³) with sequential cold surge flows and the intensified tropical trade easterlies linked to the occurrence of the northwestern Pacific explosive cyclone were illustrated in section 3—a Philippine CSV (HRF₂³) into a peninsular Malaysia HRF₂³ cyclone/event and a Borneo CSV(HRF₂³) into an

in situ HRF₂³ cyclone/event. The ζ^o (925 hPa) time series for these two CSV(HRF₂³) shown in Figs. 3a and 6a reveal that the specially amplified ζ^o (925 hPa) maxima continue to increase through interactions of these CSV(HRF₂³) with sequential cold surge flows across the South China Sea. Development of these CSV(HRF₂³) into their corresponding HRF₂³ cyclones/events leads to the following questions:

- 1) Developing into HRF_m³ cyclones/events, why should 44% of the parent Philippine and Borneo CSV(HRF_m³) undergo multi-interactions with sequential cold surge flows?
- 2) Can the HRF_m³ cyclones/events become more intense and produce more rainfall through triple maximum

FIG. 8. As in Fig. 5, but for a Borneo CSV(HRF₂³) shown in Fig. 6.

$\zeta^o(925\text{ hPa})$ than HRF_m² cyclones/events through double maximum $\zeta^o(925\text{ hPa})$ over the same rainfall centers?

- 3) What is the dynamic–hydrologic–thermodynamic role played by the second interaction of CSV(HRF_m³) with a cold surface flow in the development of HRF_m³ cyclones/events?

a. Question 1

The occurrence ratios of HRF_m³/HRF_m² events on both sides of the South China Sea can be estimated with Fig. 1. West of the SCS, 47 of 83 HRF_mⁿ events (~57%) occurred over the rainfall centers in central Vietnam and peninsular Malaysia. East of the SCS, 32 of 57 HRF_mⁿ events (56%) occurred over the rainfall centers of Borneo and Java. The western HRF_m³ cyclones/events developed from the remotely originated Philippines and Borneo CSV(HRF_m³), while the eastern HRF_m³ cyclones/events over Borneo and Java developed from the Borneo in situ CSV(HRF_m³). Regardless of their propagation distances, HRF_m³ events over the rainfall centers on both sides of the South China Sea developed from CSV(HRF_m³) with their life cycle ≥ 6 days (indicated by vertical yellow stripes in Fig. 1). In contrast, a great majority of the HRF_m² events developed from CSV(HRF_m²) 4–6 days

after these vortices formed, although some ($\sim 1/3$) central Vietnam HRF₂² events formed within 3–4 days. A majority of the CSV(HRF_m³) intensified by the second interaction with a cold surge flow occurred within 3–5 days after their parent CSV(HRF_m³) formed. The time needed for a CSV(HRF_m³) to form an HRF_m³ can be summarized by a clear stratification of the time frame (Fig. 9) from the CSV(HRF_m³) formation to the HRF_m³ occurrence as follows: 1) second maximum intensity of CSV(HRF_m³) < 4 days (3–5 days), 2) HRF₁² events approximately 2 days (1–4 days), 3) HRF₂² events approximately 5 days (4–6 days), 4) HRF₂² events ≥ 6 days (6–8.5 days), and 5) HRF₃³ events ≥ 8.5 days (8.5–10 days).

Observed by Chen et al. (2004, their Fig. 3), the averaged occurrence frequency of the East Asian cold surge is about 4.5 (6) days during the warm (cold) ENSO phase. Based on these statistics, CSV(HRF) may develop in the two following ways:

- 1) For the first 3–5 days, this CSV(HRF_m³) may survive and interact with the next cold surge flow to develop the second maximum intensity for this vortex. For the next couple of days after this interaction, the intensified CSV(HRF_m³) may lead to the following three possible developments: (i) demise; (ii) maintenance of its interaction with the second aging cold surge flow

FIG. 9. Schematic diagram to illustrate the times used by a $\text{CSV}(\text{HRF}_m^n)$ from its formation location to reach the formation location of the corresponding HRF_m^n event and the location of second maximum intensity of $\text{CSV}(\text{HRF}_m^3)$; n and m of $\text{CSV}(\text{HRF}_m^n)$ are the occurrence number of maximum ζ^o (925 hPa) and the interaction number of $\text{CSV}(\text{HRF}_m^n)$ with sequential cold surge flows for the $\text{CSV}(\text{HRF}_m^n)$ development into an HRF_m^n event.

until this $\text{CSV}(\text{HRF}_2^3)$ is intensified by the strengthened tropical trade easterlies related to the north-western Pacific explosive cyclone, to form an HRF_2^3 event, or (iii) interaction with the third cold surge flow and the intensified tropical trade easterlies, as the second possible development of $\text{CSV}(\text{HRF}_2^3)$, to form an HRF_3^3 event. The third possible development only occurred four times over the 1979–2013 period.

- 2) For the next 4–6 days after its first interaction with a cold surge flow, the $\text{CSV}(\text{HRF}_m^2)$ may have the three possible developments as $\text{CSV}(\text{HRF}_2^3)$, except without a relay interaction with the second cold surge flow.

Based on our answer to question 1, it becomes clear the formation of either HRF_m^2 or HRF_m^3 event is determined by two basic factors: the time span of the parent $\text{CSV}(\text{HRF}_m^n)$ life cycles and the occurrence frequency of East Asian cold surge flows.

b. Question 2

The intensity of the parent $\text{CSV}(\text{HRF}_m^n)$ and their corresponding HRF_m^n cyclones/events may be measured by vorticity and rainfall. The vorticity, ζ^o (925 hPa) for all parent $\text{CSV}(\text{HRF}_m^n)$ of 181 DFO HRF_m^n events and rainfall, and P^o , 6 h prior to reaching the maximum intensity over the life cycles of these $\text{CSV}(\text{HRF}_m^n)$, are shown in Fig. 10.

1) VORTICITY

Shown in Fig. 10a, six of nine HRF event groups develop from $\text{CSV}(\text{HRF}_m^n)$ through multi-interactions with sequential cold surge flows. Regardless of their future developments into either HRF_m^2 or HRF_m^3 events, intensities of their parent $\text{CSV}(\text{HRF}_m^n)$ are very close to each other, when they first form. Nevertheless, the intensity of HRF_m^3 cyclones/events may increase 20%–40%, while that for HRF_m^2 cyclones/events is intensified by only 10%–25%. Developing ultimately into HRF_m^3 events, their parent $\text{CSV}(\text{HRF}_m^n)$ undergo a second intensification, which generally increases the

second maximum intensity only 5%–10%, smaller than the intensity for the HRF_m^2 cyclone/event. Therefore, two important features of the $\text{CSV}(\text{HRF}_m^n)$ intensification for both HRF_m^3 and HRF_m^2 events should be recognized:

- (i) As pointed out in our answer to question 1, it takes 1–2 more days for a $\text{CSV}(\text{HRF}_m^2)$ to form an HRF_m^2 event than the time for a $\text{CSV}(\text{HRF}_m^3)$ to reach its second maximum intensity. The time period of 1–2 more days seems crucial for the HRF_m^2 cyclone/event to further intensify.
- (ii) The $\text{CSV}(\text{HRF}_m^3)$ may dissipate/demise, if there are no second interactions of these $\text{CSV}(\text{HRF}_m^3)$ with cold surge flows. Apparently, the relay interaction for $\text{CSV}(\text{HRF}_m^3)$ is an indispensable step in developing HRF_m^3 cyclones/events.

2) RAINFALL

The rainfall amounts produced by $\text{CSV}(\text{HRF}_m^n)/\text{HRF}_m^n$ events against their interaction frequency with cold surge flows for nine groups of HRF_m^n events are shown in Fig. 10b. Salient features of this figure may be highlighted as follows:

- (i) HRF_m^3 events produce more rainfall than HRF_m^2 events. Rainfall produced by HRF_m^3 cyclones/events is about 400%–500% more than their parent $\text{CSV}(\text{HRF}_m^3)$ produce, while HRF_m^2 cyclones/events produced only about 300%–450% more. HRF_m^2 cyclones/events produced about 40%–80% more rainfall than $\text{CSV}(\text{HRF}_m^3)$, when they reach their second rainfall maxima. Responses for $\text{CSV}(\text{HRF}_m^3)$ in rainfall production over their life cycles and the relay interaction to develop HRF_m^3 events resemble their vortex intensity change.
- (ii) Despite the interaction frequency of $\text{CSV}(\text{HRF}_m^n)$ with cold surge flows, rainfall produced by HRF_m^n events north of 8°N (including central Vietnam and the Philippines) and the HRF_m^n (PM) events is larger than that produced south of 8°N (including peninsular Malaysia, Borneo, and Indonesia). This north–south differentiation in this HRF rainfall production may be attributed to two important elements of the southeastern Asia surface circulation: the island-chain and the near-equator troughs. The former trough facilitates the formation of the Philippine $\text{CSV}(\text{HRF}_m^n)$ and enhances rainfall produced by HRF_m^n events over the former group of rainfall centers. The near-equator trough across Borneo provides a favorable environment for the Borneo $\text{CSV}(\text{HRF}_m^n)$ formation, but it is not as efficient as the island-chain trough to

FIG. 10. (a) Scatter diagrams for $\zeta^o(925 \text{ hPa})$ (ordinate) vs longitude (abscissa) for nine groups of CSV(HRF $_m^n$) ($n = 2, 3$ and $m = 1, 2, 3$) identified in Fig. 1. The $\zeta^o(925 \text{ hPa})$ for CSV(HRF $_m^n$) and CSV(HRF $_1^n$) are denoted by different green symbols, while $\zeta^o(925 \text{ hPa})$ for CSV(HRF $_2^n$) are marked by different gold symbols [see legend at the top right of (a)]. (b) Scatter diagrams for P^o (ordinate) vs time (abscissa) for CSV(HRF $_m^n$) and CSV(HRF $_2^n$) marked by different blue symbols and for CSV(HRF $_2^n$) are denoted by different red symbols [see legend at the top right of (b)].

facilitate the rainfall production over the latter group of heavy rainfall centers.

c. Question 3

The development of the second CSV(HRF $_m^3$) maximum intensity for the typical peninsular Malaysia and Borneo HRF $_m^3$ events through the dynamic, hydrologic and thermodynamic processes can be summarized as follows:

- 1) Illustrated by the vorticity budget in Eq. (1), the second CSV(HRF $_m^3$) intensification is accomplished by two dynamic processes— ζ_t^A (vorticity distribution) and ζ_t^V (vortex stretching). Because $\zeta + f > 0$ for

a concerned CSV(HRF), this vortex can be intensified by $\zeta_t^V \sim -\nabla \cdot \mathbf{V} > 0$ through the convergence of air mass flux.

- 2) As expressed by Eq. (2), the second CSV(HRF $_m^3$) maximum rainfall is increased/maintained by the convergence of water vapor flux [i.e., $-\nabla \cdot \mathbf{Q}$], driven by the convergence of the air mass flux indicated by Fig. 2.
- 3) The convergence of air mass flux in the low troposphere is part of the divergent circulation, which can be driven by diabatic heating, contributed partly by the heat for condensation through convection/precipitation, P . According to Eq. (6), $\chi \sim \chi_Q$ and $-\nabla \cdot \mathbf{V} \sim -\nabla \cdot \chi_Q$.

FIG. 11. Scatter diagrams of (a) $(-\nabla \cdot \mathbf{Q})^\circ$ vs P ; (b) $(-\nabla \cdot \mathbf{Q})^\circ$ vs $(-\nabla \cdot \mathbf{V})^\circ(925 \text{ hPa})$; and (c) $(-\nabla^2 \chi_Q)^\circ$ vs $(-\nabla \cdot \mathbf{V})^\circ(925 \text{ hPa})$ for nine groups of HRF_1^3 , HRF_2^3 , HRF_3^3 , and HRF_3^3 events are marked by a blue Greek cross, red cross, blue dot, and blue triangle, respectively. The second maximum intensity of $\text{CSV}(\text{HRF}_m^3)$, denoted by a green open circle, is also included for comparison. A least squares fit line projects the relationship between each group of scatters.

The interrelationship among $-\nabla \cdot \mathbf{V}$, $-\nabla \cdot \mathbf{Q}$, P , and $-\nabla \cdot \mathbf{V}_Q$ to intensify the second $\text{CSV}(\text{HRF}_m^3)$ maximum intensity is illustrated in Fig. 2.

For all HRF_m^3 and HRF_m^2 events occurring over the same rainfall center, the three budgets 6 h prior to the $\text{CSV}(\text{HRF})$ necessary to form the $\text{HRF}_m^3/\text{HRF}_m^2$ events are shown in Fig. 11 and characterized by the following salient features:

- 1) For both HRF_m^3 and HRF_m^2 events, the linear relationship between two variables shown in Fig. 2 emerges from all groups.
- 2) Before the formation of HRF_m^3 events, the linear relationships between two variables also appears six hours before the second maximum intensity of its parent $\text{CSV}(\text{HRF}_m^3)$. The only exception for these linear relationships is all concerned variables are smaller in their magnitudes than both HRF_m^3 and HRF_m^2 events.

Results in Fig. 11 reveal two important implications:

- 1) The dynamical, hydrological, and thermodynamical processes in developing the second intensification of $\text{CSV}(\text{HRF}_m^3)$ resemble those involved with the development of HRF_m^3 and HRF_m^2 events. Despite the fact the second interaction of the $\text{CSV}(\text{HRF}_m^3)$ is unable to develop into an HRF_m^3 event, this interaction plays a relay role crucial to develop HRF_m^3 events.
- 2) Every process involved in the development of HRF_m^2 events is quantitatively larger/stronger than that for developing the $\text{CSV}(\text{HRF}_m^3)$ second intensification. The development/intensification of HRF_m^3 events cannot be achieved without the second intensification.

5. Requirements for the HRF cyclone/event formation

Two basic requirements needed for the formation of HRF cyclones/events in central Vietnam (Chen et al. 2012a,b) and Malaysia (Chen et al. 2013a,b), including peninsular Malaysia and Borneo are the following:

FIG. 12. (left) A scatter diagram for the synchronization occurrence dates of all DFO HRF_m^n events (abscissa) and the northwestern Pacific explosive cyclone (ordinate) during the time period of October–February over 1979–2012 for nine groups of HRF_m^n events indicated by different symbols in the top-left corner. (right) A scatter diagram for the dates of $\text{CSV}(\text{HRF}_m^3)$ reaching the second maximum intensity (abscissa) vs the dates of the northwestern Pacific explosive cyclone (ordinate) close to the former event. Symbols for different groups of $\text{CSV}(\text{HRF}_m^3)$ at their second maximum intensity are represented by different color symbols at the bottom-right corner.

- 1) Occurrence synchronization for formations of the HRF_m^n event and the northwestern Pacific explosive cyclone.
- 2) Occurrence simultaneity of maximum speeds in three synoptic elements: (i) easterlies of the HRF_m^n cyclone/event, (ii) tropical trade easterlies of the North Pacific subtropical anticyclone, and (iii) westerlies of the northwestern Pacific explosive cyclone.

Requirement 1 for this HRF_m^n event formation has an important synoptic implication for the midlatitude–tropic interactions through the East Asian cold surge flow and the open ocean cold air outbreak flow in the North Pacific. These interactions are realized through intensification of the tropical trade easterlies by the open ocean cold air outbreak flow to the tropical Pacific and the merger of tropical trade easterlies with the East Asian cold surge flow to facilitate the HRF_m^n formation. The HRF_m^n event can be formed through the $\text{CSV}(\text{HRF}_m^n)$ multi-interactions with sequential cold surge flows. Can these HRF_m^2 and HRF_m^3 events occur when the westerly flow of the northwestern Pacific explosive cyclone, the tropical trade easterlies of the North Pacific subtropical anticyclone, and the easterly flow of the HRF_m^n cyclone reach their maximum speeds simultaneously to meet requirement 2?

Shown in Fig. 2 of Part I, 181 HRF_m^n events developed from their parent $\text{CSV}(\text{HRF}_m^n)$ formed in the Philippine

vicinity and Borneo. As can be inferred from trajectories of these $\text{CSV}(\text{HRF}_m^n)$ originating in these two regions to seven rainfall centers and the environment flow patterns in different seasons, the steering mechanisms of parent $\text{CSV}(\text{HRF}_m^n)$ to different rainfall centers may be different. The following questions are raised by this observation:

- 1) Can the two basic requirements for the formation of HRF_m^n events in central Vietnam and Malaysia be met by all HRF_m^n events around the South China Sea?
- 2) The development of HRF_m^3 events always go through a second interaction of their parent $\text{CSV}(\text{HRF}_m^3)$ with cold surge flow to attain their second maximum intensity. Why does not the $\text{CSV}(\text{HRF}_m^3)$ at this stage develop into an HRF_m^3 event?

a. Question 1

1) OCCURRENCE SYNCHRONIZATION OF HRF_m^n EVENT AND EXPLOSIVE CYCLONE

Following Chen et al. (2012a, 2013a), the scatter diagram of the occurrence dates (ordinate) for all 181 HRF_m^n events versus formation dates (abscissa) of the corresponding northwestern Pacific explosive cyclones is shown in the left of Fig. 12. All HRF_m^n events are distinguished by different symbols in the top-left corner. Regardless of the

parent CSV(HRF_m^n) interaction frequency with cold surge flows, the occurrence synchronization with explosive cyclones holds for about 92% of the HRF_m^n events. Only 14 HRF_m^n events ($\sim 8\%$) are 1–2 days behind the formation dates of the corresponding cyclones. These 14 HRF_m^n events are randomly distributed in different groups of HRF_m^n events.

All 79 HRF_m^3 events develop through their parent CSV(HRF_m^n) multi-interactions with sequential cold surge flows. For the second interaction of a parent CSV(HRF_2^3) with a cold surge flow, a relay intensification of this vortex is needed for it to become an HRF_m^3 event. However, the second interaction of this CSV(HRF_m^3) does not suffice its development into an HRF_2^2 event. Shown in the right scatter diagram of Fig. 12, the second intensification of the CSV(HRF_m^3) to reach its second maximum intensity is 2–3 days prior to the formation of the northwestern Pacific explosive cyclone. Apparently, the CSV(HRF_m^3) second peak intensity is not synchronous with the northwestern Pacific explosive cyclone formation. The lack of this occurrence synchronization does not allow the basin-scale circulation over the North Pacific to develop a favorable synoptic condition for this CSV(HRF_m^3) to form an HRF_2^2 event.

Shown in Fig. 13, the winter [December–February (DJF)]-mean cyclonic shear flow along the northwestern part of the cyclonic cells centered at southwestern Borneo where the near-equator trough penetrates, provides a positive vorticity zone. Additionally, indicated by the 850-hPa streamfunction [$\psi(850 \text{ hPa})$] distribution, a north–south-oriented shallow/weak trough line exists in the South China Sea. These two special seasonal-mean low-tropospheric circulation elements develop a favorable environment for the second intensification of CSV(HRF_m^3) across the South China Sea. The location distribution of the second maximum intensity of CSV(HRF_m^3) in Fig. 13 confirms this inference.

2) OCCURRENCE SIMULTANEITY OF MAXIMUM SPEEDS BY THREE SYNOPTIC ELEMENTS

For convenience, let u_{PEC} , u_{TTW} , and u_{HRF} represent, respectively, the westerlies of the northwestern Pacific explosive cyclone, the tropical trade easterlies of the North Pacific subtropical anticyclone, and the easterlies of the HRF cyclone/event. Using 18 HRF_m^n events for nine rainfall centers as examples, the $u_{\text{PEC}}(850 \text{ hPa})$ westerly time series and the $u_{\text{TTW}}(850 \text{ hPa})$ easterly time series at the longitude location of maximum $u_{\text{PEC}}(850 \text{ hPa})$ westerlies and the $u_{\text{HRF}}(850 \text{ hPa})$ easterly time series at the longitude location of maximum $u_{\text{HRF}}(850 \text{ hPa})$ easterlies for HRF_m^n events are displayed in Fig. 14a. The formation dates of explosive cyclones and HRF cyclones/events coincide with the maximum $u_{\text{TTW}}(850 \text{ hPa})$ date and are

FIG. 13. The winter (DJF)-mean $\psi(850 \text{ hPa})$ chart superimposed with $\zeta(850 \text{ hPa})$ (pink shading) and locations of the CSV(HRF_m^3) second maximum intensity (marked with different symbols on the bottom right-hand side of the figure), the island-chain trough, the South China Sea trough, and the near-equator trough (Johnson and Houze 1987; Johnson 2005). The troughs are marked by dashed blue lines.

confirmed by the occurrence simultaneity of maximum speeds for u_{PEC} westerlies, and for easterlies of u_{TTW} and u_{HRF} , when the corresponding HRF_m^n event occurs. To verify the occurrence simultaneity of these three zonal speeds for all cases of HRF_m^n events, two different approaches are adopted to perform this verification:

- A manual approach: The three maximum zonal speeds (u_{PEC} , u_{TTW} , and u_{HRF}) of all HRF events are connected to check whether these three zonal speeds reach a maximum simultaneously. Occurrences of 14 HRF_m^n events that do not synchronize with those of explosive cyclones are confirmed by this approach.
- Correlation coefficient approach: Using the three correlation coefficients $\sigma(u_{\text{HRF}}, u_{\text{PEC}})$, $\sigma(u_{\text{HRF}}, u_{\text{TTW}})$, and $\sigma(u_{\text{HRF}}, u_{\text{TTW}})^1$ as three axes, the three-dimensional scatter diagrams for these three correla-

¹ When u_{HRF} , u_{PEC} , and u_{TTW} reach their maximum values on the date of the HRF event, they are given a value of 3. If the value of any u has its maximum at 1 (2) day(s) ahead of the related HRF event, this variable is given a value of 2 (1), and if the maximum is 1 (2) day(s) behind the HRF event, the value is 4 (5). The time series for these numerical values is used to generate correlation coefficients between two time series. The correlation coefficient value of 1 should be obtained, if two time series have only values of 3. If these two time series have values other than 3, the correlation coefficient value should be smaller than 1.

FIG. 14. (a) Time series for $u(850\text{ hPa})$ at the location of the maximum isotach for three synoptic systems: the southern rim of the northwestern Pacific explosive cyclone (u_{PEC} ; dark blue line), the tropical trade easterlies (u_{TTW} ; red line) corresponding to the location of u_{PEC} , and north of the HRF cyclone (u_{HRF} ; green line) for selected eighteen HRF_m^n events in nine rainfall centers. The occurrence dates for explosive cyclones and HRF_m^n cyclones/events are marked by red and dark blue crosses, respectively. (b) Three-dimensional scatter diagrams of correlation $\sigma(u_{\text{HRF}}, u_{\text{PEC}})$, $\sigma(u_{\text{PEC}}, u_{\text{TTW}})$, and $\sigma(u_{\text{HRF}}, u_{\text{TTW}})$ for nine groups of HRF_m^n events; one blue dot represents a group. These HRF_m^n events are classified into four groups, HRF_1^1 , HRF_2^2 , HRF_2^3 , and HRF_3^3 , and projected on the three three-dimensional scatter diagrams.

tion coefficients for four types of HRF_m^n events shown in Fig. 14b vary between 1 and 0.9.

The occurrence simultaneity for the maximum easterlies of u_{HRF} and u_{TTW} , and westerlies of u_{PEC} is met by a great majority ($\geq 92\%$) of HRF events, regardless of the interaction frequency of their parent CSV(HRF) with cold surge flows.

b. Question 2

Because 79 HRF_m^3 events are identified, one may question whether the basic requirements for the formation of HRF_m^n events around the South China Sea can be

met by the intensification of $\text{CSV}(\text{HRF}_m^3)$ to reach their second maximum intensity (prior to formation of the HRF_m^3 event). It was shown in Fig. 12 that no single northwestern Pacific explosive cyclone occurrence synchronizes with the occurrence of the $\text{CSV}(\text{HRF}_m^3)$ second maximum intensity. The basin-scale synoptic environment favorable for the HRF_m^n event formation is developed by the occurrence synchronization of the HRF_m^n event and the northwestern Pacific explosive cyclone. The occurrence simultaneity of maximum easterlies of u_{HRF} and u_{TTW} , and westerlies of u_{PEC} cannot be met by the $\text{CSV}(\text{HRF}_m^3)$, when it reaches its second maximum

peak intensity. The favorable basin-scale synoptic environment for CSV(HRF_m³) at its second maximum intensity to form an HRF_m³ event does not develop. Nevertheless, the intensification of a CSV(HRF_m³) to reach its second maximum peak intensity is an indispensable process for the development of a CSV(HRF_m³) into an HRF_m³ event, but not possibly to directly develop into an HRF_m³ cyclone/event.

6. Summary and concluding remarks

Shown in Fig. 1, the life cycle of a CSV(HRF_mⁿ), the time from its formation to the occurrence of the corresponding HRF_mⁿ event, may be 1–4 days over the Philippine rainfall center and 3–9 days for other rainfall centers (including central Vietnam, peninsular Malaysia, south-eastern Sumatra, Java, and Borneo) around the South China Sea. The occurrence frequency of the East Asian cold surge is about 4.5 (6) days on the average during the warm (cold) ENSO phase (Chen et al. 2004). Thus, the development of CSV(HRF_mⁿ) into HRF_mⁿ events should be achieved through their multi-interactions with cold surge flows, one to three times.

The 925-hPa vorticity averaged over the area around a CSV(HRF) with $\zeta \geq 1.8 \times 10^{-5} \text{ s}^{-1}$, $\zeta^o(925 \text{ hPa})$, is used as an indicator of the CSV(HRF) intensity. Tracking CSV(HRF) for 181 DFO HRF events during the 1979–2012 period, the $\zeta^o(925 \text{ hPa})$ time series of CSV(HRF_mⁿ) over their life cycles are prepared with the Lagrangian approach. The peak intensity of CSV(HRF_mⁿ) interacting with the cold surge flow is well reflected by the detrended peak $\zeta^o(925 \text{ hPa})$ value $\geq$ one standard deviation of the detrended $\zeta^o(925 \text{ hPa})$ time series. Based on this approach, two groups of 181 HRF events are categorized:

- 1) The 102 HRF_m² events develop from two different processes: (i) The 41 HRF₁² events, developed from the Philippine CSV(HRF₁²), interact with the same PHS-type cold surge during (their) formations and formations of HRF₁² events. (ii) The 61 HRF₂² events developed from CSV(HRF₂²), which form by the interactions of original perturbations with one cold surge and later evolve into HRF₂² events by interacting with another sequential cold surge flow.
- 2) The 79 HRF_m³ events developed from their parent CSV(HRF_m³) interacting with two or three sequential cold surge flows. The second peak intensity of a CSV(HRF_m³) by its interaction with the second cold surge flow serves as a relay intensification of the CSV(HRF_m³) to form an HRF_m³ event.

The development of HRF_m² involved interactions with the same or another cold surge flow, respectively, while

the development of HRF_m³ is involved with two or three different cold surge flows in sequence. The reasons for HRF_m³ events to need one extra interaction with a cold surge flow are the following:

- 1) The life cycles for all 79 CSV(HRF_m³) to form HRF_m³ events are ≥ 6 days, longer than the occurrence frequency of the East Asian cold surges.
- 2) The life cycle of CSV(HRF_m²) is 4–6 days, but those for CSV(HRF_m³) to reach its second maximum intensity is about 3–5 days, shorter than CSV(HRF_m²) to form HRF_m² events.
- 3) A shallow-weak surface trough along the northeast–southwest axis of the South China Sea facilitates the second peak intensification of CSV(HRF_m³).

The basic difference in the development processes between HRF_m³ and HRF_m² events lies with the former group, which has the relay interaction of CSV(HRF_m³) with the second sequential cold surge flow.

The roles played by the second maximum intensity of CSV(HRF_m³) to develop HRF_m³ events are as follows:

- 1) The time (3–5 days) for a CSV(HRF_m³) to reach its second maximum peak intensity is shorter than that for the CSV(HRF₂²) to form an HRF₂² event. Thus, the westward-propagating CSV(HRF_m³) attain their second maximum peak intensity in the middle of the South China Sea.
- 2) CSV(HRF_m³), at its second peak intensity, cannot satisfy the two occurrence requirements for HRF₂³ events: (i) synchronization of the CSV(HRF_m³) second peak intensity with the formation of the northwestern Pacific explosive cyclone, and (ii) occurrence simultaneity of maximum speeds by the explosive cyclone westerlies, tropical trade easterlies of the North Pacific anticyclone, and easterlies of the CSV(HRF₂³) at its second peak intensity. Thus, the basin-scale synoptic environment cannot develop a favorable environment to allow this CSV(HRF₂³) at its second peak intensity develop into an HRF₂³ event.
- 3) The second maximum intensity of the CSV(HRF₂³) enables itself to evolve into an HRF₂³ cycle/event whose intensity and rainfall are generally larger than that for the HRF₂² cyclone/event. Thus, the relay interaction of the CSV(HRF₂³) is an indispensable step for this vortex to develop into an HRF₂³ event.

The identification for the two groups of HRF_mⁿ events in their development reveals several unique features of these HRF_mⁿ cyclones/events:

- 1) The development of HRF₁² events over the northern and southern Philippines are involved only by the interaction of the Philippine CSV(HRF₁²) with one

PHS-type cold surge flow and the two aforementioned requirements of the basin-scale environment for the formation/occurrence of HRF. The development of this CSV(HRF₁²) has not attracted any attention, yet. Further research efforts are needed to explore the development mechanism of the Philippine HRF₁² event.

- 2) Most of the super-HRF (with maximum rainfall $\geq 500 \text{ mm day}^{-1}$) events ($\sim 75\%$) in Vietnam are HRF₂³ events. Some super-HRF events in Vietnam are HRF₂² events, but the population ratio is much lower ($\sim 15\%$ of HRF₂² events).
- 3) The development of synoptic disturbances through three consecutive forcings, as the multi-interactions with sequential cold surge flows, has not been identified in any region of the globe.

These unique features of CSV(HRF_mⁿ) development into HRF_mⁿ events also lead us to face new research challenges:

- 1) The development of the Philippine HRF₁² event is very different from the other two groups of HRF events. How do the Philippine HRF₁² events develop from the Philippine CSV(HRF₁²) through their interaction with only one PHS-type cold surge flow?
- 2) The development of the HRF_mⁿ event around the South China Sea is attributed to the midlatitude–tropic interactions through the East Asian cold surge flows. In midlatitudes, the occurrence of the East Asian cold surge flow is juxtaposed between the surface high and low of a dipole in northeastern Asia. The tropical trade easterlies are intensified by the cold air outbreak in the open ocean linked to the formation of the explosive cyclone. In the tropics, the formation of CSV(HRF_mⁿ), the intensification of CSV(HRF_m³) to reach its second peak intensity, and the formation of HRF_m³ events are achieved through the multi-interactions of the parent CSV(HRF) with the East Asian cold surge flows. The difficulty to forecast the occurrence of HRF_m³ events is attributed to the accuracy of coherent predictions for the related synoptic activities in both midlatitudes and the tropics.

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