Forecast Advisory for a Cold-Season Heavy Rainfall/Flood Event That Developed from Multiple Interactions of the Cold-Surge Vortex with Cold-Surge Flows in the South China Sea^①

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ABSTRACT

The peak intensity occurrence frequency over the life cycles of parent cold-surge vortices (CSVs) for heavy rainfall/flood (HRF) events is classified into two types depending on their life cycles having two or three peak intensities, denoted as HRF² or HRF³, respectively. The formation of an HRF² event from its parent CSV(HRF²) formation is ≤ 5 days, while the formation of an HRF³ event is ≥ 6 days. The latter group contributes $\sim 57\%$ of the total number of HRF events. As a result of some model constraints, the formation and development of HRF³ events are not well forecasted by the Global Forecast System (GFS) and regional forecast models. The life cycle and second peak intensity for CSV(HRF³) allow for the introduction of a forecast advisory for HRF³ events. Identification of CSVs and two sufficient requirements for the formation and occurrence of HRF events were developed by previous studies. Nevertheless, two new necessary steps are now included in the proposed forecast advisory. The population ratio for CSV(HRF³) and the regular CSV is only about 15%. The occurrence optimum time t_o for the CSV(HRF³) second peak intensity from this vortex formation is about 3 days 6 h. The GFS forecast over t_o is utilized to identify CSV(HRF³). Then, the relay of the GFS forecast from the occurrence time of the CSV(HRF³) second peak is used to predict the formation/occurrence of HRF³ events. Six HRF³ events during cold seasons for 2013–16 are used to test the feasibility of this forecast advisory. Results clearly demonstrate this advisory is a success for the forecast of HRF³ events over the entire life cycles of their parent CSV(HRF³)s.

1. Introduction

The most hazardous weather in winter around the South China Sea (SCS) is from heavy rainfall/flood (HRF) events, for example, the 2008 Hanoi event (31 October 2008) in north Vietnam (BBC 2008), the 2008 Kuantan event (29 November 2008) in the Malaysian Peninsula

(Reliefweb 2009), and many others. Accurate forecasts for HRF events are important for the life, property, and commerce of Southeast Asians living around the SCS. To test the effect of local topography on the rainfall distribution of an HRF event over the east coast of Peninsular Malaysia, Juneng et al. (2007) used the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) to make 4-day forecasts for an HRF event (9–11 December 2004). The life cycle of this event, beginning from the formation of a cold-surge vortex (CSV) and its development into an HRF event in Borneo, is 7 days (4–10 December 2004). Using Colorado State University's Regional Atmospheric Modeling System (Cotton et al. 2003), Truong et al. (2009) tested the impact

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of different parameterization schemes on the 2-day precipitation forecast of an HRF event in central Vietnam (24–26 November 2004). The life cycle for this HRF event is 6 days from its parent CSV that formed in the vicinity of the Philippines. Application of regional forecast models to predict the occurrence of HRF events over regions around the SCS faces two constraints: 1) the limited domain may reduce the ability to accurately depict the extratropical–tropical and global/hemispheric–regional interactions of the weather systems of interest and 2) the limited forecast time may reduce the forecastability for the long-duration development from the CSV formation to the occurrence of the HRF event.

Shown in Fig. 1, 146 HRF events (not including the 41 HRF events over the Philippines) are identified over 37 cold seasons (October–February) during 1979–2016. Only 11 of these HRF events that developed from formations of their parent CSVs (see Table A1 for a list of key acronyms used in this paper) have life cycles *shorter* than 4 days. In contrast, the other 135 HRF events, developed from their parent CSV(HRF)s, have life cycles greater than 4 days, which may exceed the time for regional forecast models to produce accurate forecasts. The National Centers of Environmental Prediction (NCEP) Global Forecast System (GFS) operationally issues 8-day forecasts (NCEP 2003). Figure 1 shows that most HRF events in central Vietnam have life cycles [from parent CSV(HRF) formations] shorter than 6 days. Utilizing the relationships of synoptic features between the extratropics and tropics, and the dynamic–hydrological relationships among three monsoon modes, Chen et al. (2012) introduced a forecast advisory to supplement the GFS 8-day forecast for the late fall HRF events in central Vietnam.

After their investigation of the formation mechanism driving cold-season, heavy rainfall centers over central Vietnam (Chen et al. 2012) and Malaysia (Chen et al. 2013a,b), Chen et al. (2015b) searched for the formation mechanism of parent CSV(HRF)s and their propagation properties over the entire SCS. The CSV(HRF)s form in two regions: 1) the Philippines vicinity along the island-chain surface trough and 2) the cyclonic shear region around the near-equatorial trough over Borneo. These CSV(HRF)s propagate westward (southwestward), if the westerly (northerly) component of the cold-surge flow inside the SCS is larger (smaller) than the northerly component. As shown in Fig. 1, 63 HRF events (~43%) need fewer than 5 days to develop from their parent CSV(HRF)s. In contrast, 83 HRF events (~57%) require *more than* 6 days to develop from the formation of their parent CSV(HRF)s. These 83 long-lived CSV(HRF)s undergo a *second* maximum intensification through their interactions with the second

cold-surge flow before the formation of their HRF events. In other words, the second peak intensity of CSV(HRF) provides a clear indication of a connection between these CSV(HRF)s with a second new cold-surge flow in the SCS. Thus, CSV(HRF)s can be classified into two groups¹:

- 1) The development of CSV(HRF²) into an HRF² event that exhibits peak intensity once at the formation of CSV(HRF²) and the HRF² event and develops in less than 5 days.
- 2) The development of CSV(HRF³) into an HRF³ event that undergoes a second peak intensity between formations of CSV(HRF³)s, and the HRF³ event is longer lived.

For convenience, we designate group 1 as CSV(HRF²) and an HRF² event, and group 2 as CSV(HRF³) and an HRF³ event.

Chen et al. (2012) developed a forecast advisory for HRF² events that form in central Vietnam, which can be applied to the development of CSV(HRF²) events around the SCS. However, a major concern in this study is to develop a forecast advisory for the development of CSV(HRF³)s into their HRF³ events. The longest life cycle for a CSV(HRF³) to develop into its HRF³ event is 10 days. The 16-day forecasts issued by the NCEP GFS (NWS/EMC 2016) with a resolution of 13 km, but posted onto a $0.5^\circ \times 0.5^\circ$ grid, show the forecastability for several aspects of CSV(HRF³) characteristics, such as location, intensity, rainfall, and occurrence time of the second peak intensity. However, the forecast accuracy is reduced significantly after the first 3–5 days. It may *not* be feasible to use the GFS 16-day forecasts for the development or formation of HRF³ events over the entire life cycle of its parent CSV(HRF³) around the SCS. To overcome this limit of GFS forecastability, a forecast advisory is introduced to use the connection between the HRF³ event from the formation of its parent CSV(HRF³) to the second peak intensity and from this peak intensity to the formation of HRF³ events.

The feasibility of the proposed forecast advisory, referred to as relay forecasts for the entire life cycle of CSV(HRF³) to the formation of the HRF³ events, is described in the following manner. Reanalysis data generated by the NCEP GFS since 2006, by ECMWF-Interim over 1979–2006, by GFS forecasts for HRF³ events since 2006, and for some special cases before 2006 are described in section 2. Observations and forecast statistics for various aspects of the CSV(HRF³) second

¹ An example for each group of CSV(HRF)s is shown in online supplement 1.

FIG. 1. The life cycle/time needed by a CSV(HRFⁿ) to develop from its formation location and reach the formation location of the HRFⁿ event in seven rainfall centers, superscript n is either a 2 or a 3. Travel time is projected onto the abscissa and the case numbers of HRFⁿ events are scaled along the ordinate. All (187) HRF events are classified into two groups, HRF³ and HRF², and are denoted by a solid triangle and dot, respectively. The latter group also includes HRF² events developed from CSV(HRF²)s, which interact with only one cold-surge flow of the Philippine Sea (PHS) type, marked by a short line with a dot located at the center. An open circle denotes the second peak intensity for CSV(HRF³). The red (blue) symbol indicates the CSV(HRFⁿ) interaction with the SCS (PHS)-type cold-surge flow. The green and yellow strips stratify the times needed to develop the second peak intensity of CSV(HRF³), and to form HRF² and HRF³ events, respectively. Covering 37 cold seasons (1979–2016), this figure is a modified version of Chen et al.'s (2015a) Fig. 1, which includes 36 cold seasons (1979–2015).

peak intensity are presented in section 3. Results from this section for the formations of both CSV(HRF³)s and their second peak intensity are compiled and utilized to develop a forecast advisory, as well as relay forecasts for the occurrence of HRF³ events. An illustration of the proposed forecast advisory for HRF³ events around the

SCS and the feasibility test for this forecast advisory are presented in section 4. A summary for relay forecasts produced by the forecast advisory for the development of CSV(HRF³)s and formation of HRF³ events, along with suggestions for future study, are offered in section 5.

2. Data and identification of CSV and CSV(HRF)

Data sources used in this study include rainfall, reanalysis, daily surface analysis maps, HRF events, and depictions of explosive cyclones. Details of these data sources are presented in Table 1. The analysis performed with observations covers the 1979–2016 period. The data quality and amount are sufficient in terms of uniformity and abundance, a necessary condition for analysis over this 37-yr period. Except for rainfall, the last four data sources meet this requirement.

Two data sources (WMO stations, APHRODITE) provide information on rainfall over land, while another two data sources (TRMM, PERSIANN) furnish rainfall amounts over both land and ocean. Different periods and regions are covered by these rainfall data. To make the rainfall data uniform over the analysis region, a simple calibration procedure is adopted to prepare them. Based on the information from the rainfall datasets provided in Table 1, this procedure includes the following steps²:

- 1) The TRMM rain $P(\text{TRMM})$ measurements are calibrated against the APHRODITE rainfall by determining the ratio between these two rainfall datasets over Japan, where $P(\text{calibrated TRMM}) \simeq 1.2 P(\text{TRMM})$.
- 2) The PERSIANN rainfall is calibrated against $P(\text{calibrated TRMM})$ for 1983–97 with $P(\text{calibrated PERSIANN}) = 1.2 \times P(\text{PERSIANN})$.
- 3) The $P(\text{calibrated TRMM})$ and $P(\text{calibrated PERSIANN})$ are combined over their available period of rainfall data, as shown in Table 1.

The major weather systems concerned in this study are CSVs, CSV(HRF³)s, HRF³ events/cyclones, and northwest Pacific (NWP) explosive cyclones. These weather systems are identified by the following approaches and data sources.

- 1) CSV: Two reanalysis data sources (NCEP GFS and ERA-Interim) are used to generate streamline charts. These charts, prepared with NCEP GFS analysis data, match the blackbody brightness temperature T_{BB} and/or rainfall distribution more closely in detail than does the ERA-Interim analysis. The GFS analysis with a $0.5^\circ \times 0.5^\circ$ resolution became available in 2006. Before this year, streamline charts were prepared with the ERA-Interim reanalysis of $0.5^\circ \times 0.5^\circ$. These streamline charts are supplemented with daily surface analysis maps

issued by NCEP's Service Records Retention System (SRRS), JMA, the Thai Meteorological Department (TMD), and BOM to identify the vortices of CSVs formed in the vicinity of the Philippines by the interaction of easterly waves with cold-surge flows and the island-chain troughs. Similarly, the closed vortices of CSVs are also formed over Borneo by the interaction of cold-surge flows with orography and the near-equatorial troughs across Borneo.

- 2) CSV(HRF³): This type of CSV is originally formed as a CSV, but will develop into the HRF³ cyclone/event through three peak intensities. A special approach is developed in section 3 to separate CSV(HRF³)s from all identified CSVs using the GFS forecasts to check for their second peak intensity 3–5 days after they form like regular CSVs.
- 3) HRF³ cyclone/event: The occurrences of HRF³ events over the 1979–2016 period are identified by the Dartmouth Flood Observatory (DFO 2016)³ and the International Emerging Disaster Database (EM-DAT; CRED 2016) used in this study.
- 4) NWP explosive cyclone: Sanders and Gaykum (1980) identified this type of cyclone with a deepening rate of surface pressure $\leq -24 \text{ hPa day}^{-1}$. Observed by Chen et al. (2012), the surface pressure deepening rate of NWP explosive cyclones is underforecasted by GFS. The threshold value used to identify the NWP explosive cyclones forecasted by GFS is $\leq -15 \text{ hPa day}^{-1}$.

3. Development of HRF³ events and relay forecast for their occurrences

a. Development of HRF³ events with the second peak intensity for CSV(HRF³)

The time evolution of CSV(HRF³)s with an intensity measured by the area-averaged $\zeta(925 \text{ hPa}) \geq 1.8 \times 10^{-5} \text{ s}^{-1}$ over these vortices is marked by red crosses in Fig. 2a. The formation of HRF³ events undergoes *three* peak intensities, if the time needed for the development of their parent CSV(HRF³)s is ≥ 6 days. The *first* peak intensity for CSV(HRF³)s occurs when they form in vicinity of the Philippines and Borneo. The *second* peak intensity for CSV(HRF³)s occurs when these vortices interact with the second cold-surge flows over the SCS. The *third* peak intensity for these vortices appears when their corresponding HRF³ events develop

² The details involved with designing this procedure are presented in online supplement 2.

³ Categories of HRF³ events are provided in online supplement 3.

over the cold-season rainfall centers in central Vietnam, the Malay Peninsula, Sumatra, Java, and Borneo. In Fig. 2a, the temporal evolution of CSVs is illustrated by the intensity measured following the method used for CSV(HRF³), but marked by black dots. The populations of identified CSVs and CSV(HRF³)s feature 556 and 83 cases, respectively.

The mean intensity of CSVs depicted by the third-order polynomial regression line (NCAR 2016) increases to reach a peak value on day 6, but then dissipates by day 7. In contrast, the CSV(HRF³) evolution exhibits an increasing trend to day 8 for most HRF³ events. The second peak intensity of CSV(HRF³)s, marked by open circles with different colors, occurs during days 3–5 (Fig. 2a). As shown in Fig. 1, the third peak intensity for CSV(HRF³), the formation of the HRF³ event marked by an open color triangle, starts to form on day 6. They distinctly project well above the third-order polynomial regression line of the CSV(HRF³) time series. These second peak intensities are generally smaller than the third peak intensities for HRF³ events. However, the former is an indispensable process for CSV(HRF³)s to develop into HRF³ events on day 6 and to make the intensity of HRF³ events larger than those for HRF² events (Chen et al. 2015a). Additionally, the formation of HRF³ events needs to meet another two requirements (Chen et al. 2015a): 1) occurrence synchronization of an HRF³ event with an NWP explosive cyclone and 2) simultaneous occurrence of maximum speeds by westerlies of the HRF³ cyclone, tropical trade easterlies of the North Pacific (NP) subtropical anticyclone, and westerlies of the NWP explosive cyclone.

As observed in Chen et al. (2012), the occurrences of central Vietnam HRF events are synchronized with the formation of the majority ($\sim 2/3$) of NWP explosive cyclones, which directly develop from the northeast Asian surface lows coupled with the cold-surge flows involved in the formation of their parent CSV(HRF)s. A relationship between these NWP explosive cyclones and HRF³ events is hypothesized. Figure 3 shows that 7 of the 83 HRF³ events ($>8\%$) are synchronized with the NWP explosive cyclones that directly developed from the northeast Asian surface lows related to the formation of their parent CSV(HRF³). In contrast, 49 occurrences of 83 HRF³ events (59%) synchronize with formations of NWP explosive cyclones, which develop from the northeast Asian surface lows involved with the intensification process of the CSV(HRF³) second peak intensity. Only 27 occurrences of 83 ($\leq 33\%$) HRF³ events synchronize with the formation of the corresponding NWP explosive cyclones developed from surface lows that originated over the leeside of the Altai Mountains

northwest of Mongolia. As is shown in Fig. 3, the CSV(HRF³)'s second peak intensity is not only crucial to the formation of an HRF³ event, but also is closely related to the synchronous formation of an NWP explosive cyclone with the formation of an HRF³ event.

Since 2004 and 2006, the NCEP GFS has operationally issued 8- and 16-day forecasts, respectively. For 12 cold seasons during the 2004–16 period, 30 CSV(HRF³) events and 178 CSVs are identified from these GFS forecasts. We also select another five CSV(HRF³)s during 1984–2004 forecasted with the $0.5^\circ \times 0.5^\circ$ version of the GFS model and analysis used to verify the HRF forecast advisory for central Vietnam, as proposed by Chen et al. (2012). Including these five cases, we have GFS forecasts for 35 CSV(HRF³)s available for the present study. Although intensities for the GFS CSV(HRF³)s and CSVs are generally underforecasted, as depicted in Fig. 2b, the threshold value for $\zeta(925 \text{ hPa}) \geq 1.8 \times 10^{-5} \text{ s}^{-1}$ is still used to measure the forecasted intensity of vortices for these two groups. Intensity time series for these two groups of vortices are shown in Fig. 2b. From the beginning of day 1, the GFS CSV intensity exhibits a decreasing trend. From day 2 forward, no significant decreasing trend is seen until the end of day 4. Then, a significant decreasing trend appears for the next three days. By the end of day 7, these CSVs are no longer notable.

Different from the observations, the GFS CSV(HRF³)s do not exhibit a notable increasing trend until the end of day 4, but then follow a decreasing trend after the end of day 5. The second peak intensities of GFS CSV(HRF³)s appear on days 3–5 as the observations, but forecast peak intensities are weaker than the observations by more than $0.2 \times 10^{-5} \text{ s}^{-1}$. The GFS CSV(HRF³)s with their third peak intensity start to form on day 5; 11 are forecasted and form by day 5, 1 day ahead of observed HRF³ events. Thus, two sufficient requirements for the formation of HRF³ events cannot be satisfied by the GFS CSV(HRF³)s with their third peak intensity (see supplement 4 in the online supplemental material).

The second peak intensity for CSV(HRF³) is a crucial intensification process for CSV(HRF³)s that develop into HRF³ events. This peak intensity is also a practical means of distinguishing between CSV(HRF³)s and CSVs. Any procedure for improving the forecast for the occurrence of the CSV(HRF³) second peak intensity, in turn, will improve the forecast for the formation of HRF³ events. The occurrence times for the CSV(HRF³) second peak intensity are displayed in Fig. 4a from day 0. With the optimum time ≤ 3 days 6 h, the occurrence times for the GFS CSV(HRF³) second peak intensity (Fig. 4b) coincide with those for the observed CSV(HRF³)s (Fig. 4a). If this optimum time ($t_o = 3$ days 6 h)

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

Data	Source	Spatial resolution	Spatial domain	Temporal resolution	Data period	Source information
Precipitation Surface observations	WMO surface stations					http://www.ncdc.noaa.gov/oa/climate/climate_data.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	TMD, Malaysian Meteorological Department (MMD), and Indonesian Agency for Meteorological, Climatological and Geophysics (MCGAI)
	Philippines		Regional (land)	3 h	1979–present	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)
Regional satellite observations	Indonesia (Sumatra and Java)		Regional (land)	3 h	1979–present	MCGAI
	APHRODITE (version 1204R1)	0.25° lat × 0.25° lon	Asia (land)	Daily	1951–2007	Yatagai et al. (2012)
	GMS T_{BB}	1° lat × 1° lon	59.5°S–59.5°N, 80.5°E–160.5°W	3 h	1980–present	MRI
	GMS/GOES-9/MTSAT	5 km	70°S–70°N, 80°E–150°W	1 h	1979–present	MRI; Blersch and Probert (1991); MSC (1997)
Global gridded precipitation Global reanalyses (1979–present) Daily surface analysis map	TRMM ^a (3B42v7)	0.25° lat × 0.25° lon	59.5°S–59.5°N, 180°W–180°E	3 h	1998–present	Huffman and Bolvin (2015)
	PERSIANN	0.25° lat × 0.25° lon	50°S–50°N, 180°	Daily	1983–present	Ashouri et al. (2015)
	NCEP GFS	0.5° lat × 0.5° lon	Global	6 h	2006 – present	NWS/EMC (2016)
	ERA-Interim	0.5° lat × 0.5° lon	Global	6 h	1979 – present	Dee et al. (2011)
Heavy rainfall/ flood events	NCEP SRRS			12 h	1979–present	NCEI (2016)
	Northern Hemisphere surface analysis NCEP tropical strip surface analysis and observation		Northern Hemisphere tropical (40°S–40°N)			
	JMA		NWP	6 h	1979–present	http://www.jma.go.jp/en/g3/
	TMD		15°S–45°N, 65°E–150°W	6 h	2008–present	http://www.tmd.go.th/en/weather_map.php
	BOM		35°S–30°N, 70°E–180°	12 h	2000–present	http://www.bom.gov.au/australia/charts/archive/
	DFO ^b		Global		1979–present	DFO (2016)
	EM-DAT		Global		1900–present	CRED (2016)

TABLE 1. (Continued)

Data	Source	Spatial resolution	Spatial domain	Temporal resolution	Data period	Source information
Explosive cyclone	Pressure falling rate of 24 hPa day ⁻¹					
	NCEP SRRS Northern Hemisphere surface analysis		Northern Hemisphere	12 h	1979–present	SRRS (NCEI 2016)
	JMA		NWP	6 h	1979–present	http://www.jma.go.jp/en/g3/

^a According to [Huffman and Bolvin \(2015\)](#), the TRMM Microwave Imager was closed on 8 April 2015, but the 3B42 version of TRMM precipitation operates in parallel with the Integrated Multisatellite Retrievals for Global Precipitation Measurement (GPM), known as IMERG.

^b DFO severity class: class 1 (large flood events), representing significant damage to structures or agriculture and fatalities, and/or 1–2-decades-long reported intervals since the last similar event; class 1.5 (very large events), including greater than 20-yr, but less than 100-yr, recurrence intervals 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.

is adopted to forecast the CSV(HRF³) second peak intensity against the GFS forecasts every 6 h, the contrast between [Figs. 4a and 4b](#) shows the relay forecast at $t^o = t_o + t_r$ is a feasible method to filter nondeveloping CSVs, where t_r = observation time of occurrence – optimum time t_o .

The intensity and occurrence time of the second peak intensity for GFS CSV(HRF³)s ([Fig. 4b](#)) are close to the observations ([Fig. 4a](#)). The performance assessment of the GFS forecasts for the second peak intensity of CSV(HRF³)s is assessed by the forecast accuracy with some basic characteristics of CSV(HRF³)s at their second peak intensity: errors of occurrence time, intensity, location, and hydrological condition.

1) OCCURRENCE TIME

Shown in [Fig. 4a](#), the occurrence time of the second peak intensity for a great majority of the CSV(HRF³) is on days 4–5, after CSV(HRF³) formation. Using $t_o = 3$ days 6 h as the optimum time and following the relay forecasts ([Fig. 4b](#)) for the occurrence time of the CSV(HRF³) second peak intensity, the occurrence time error is zero ([Fig. 5a](#)).

2) INTENSITY

The area-averaged $\zeta(925 \text{ hPa})$ of the observed CSV(HRF³) second peak intensity for 35 identified cases is $2.64 \times 10^{-5} \text{ s}^{-1}$ ([Fig. 5b](#), bottom). The error for the GFS-forecasted CSV(HRF³) second peak intensity at $t^o = t_o + t_r$ against the area-averaged $\zeta(925 \text{ hPa})$ of 35 observation CSV(HRF³)s is 7%. Therefore, the GFS forecast bias at t^o for the CSV(HRF³) second peak intensity is acceptable.

3) CSV(HRF³) LOCATION

Observed (solid red triangle) and forecasted (open blue triangle) locations of CSV(HRF³) second peak intensity are shown in the bottom panel of [Fig. 5c](#). All 35 CSV(HRF³)s are classified into two groups: *propagating* and *trapped*. The former group consists of CSV(HRF³) CV, CSV(HRF³)PM, CSV(HRF³)BM, CSV(HRF³)PS, and CSV(HRF³)BS, while the latter group includes only CSV(HRF³)BO and CSV(HRF³)JV. The forecast location error of the *first* group is measured by the ratio between the following two distances: 1) the distance difference between the forecasted (blue open triangle) and observed (solid red triangle) locations of CSV(HRF³) second peak intensity and 2) the distance traveled by CSV(HRF³) from its formation location (red dot) to where its second peak intensity occurs. For the *second* group, CSV(HRF³)s are trapped in Borneo.

The forecasted location errors for the second peak intensity of the first CSV(HRF³) group are projected onto a clock ([Fig. 5c](#), top). These errors are less than

FIG. 2. (a) Temporal evolution of 556 CSVs (black dots) and 83 CSV(HRF³) (red crosses) depicted with $\zeta(925 \text{ hPa})$ averaged over the area of these vortices with a threshold value $\zeta(925 \text{ hPa}) \geq 1.8 \times 10^{-5} \text{ s}^{-1}$ for 37 cold seasons over the 1979–2016 period. The *second* and *third* peak intensities for CSV(HRF³) are indicated by open circles and triangles, respectively. The red line [the third-order polynomial regression line for the area-averaged $\zeta(925 \text{ hPa})$ of CSV(HRF³)] is superimposed onto a light yellow strip [one standard deviation for the area-averaged $\zeta(925 \text{ hPa})$ of CSV(HRF³)]. The blue third-order polynomial regression line superimposed on the light-blue strip is the same for CSVs. (b) As in (a), but for 178 GFS CSVs and 35 GFS CSV(HRF³)s for 12 cold seasons during the 2004–16 period.

10% and west of the observed locations. Forecast location errors for the second CSV(HRF³) group are $\sim 25 \text{ km}$ (Fig. 5c, middle).

4) HYDROLOGICAL CONDITIONS

The most important variable for the CSV(HRF³) development into an HRF³ event is rainfall P . Its

maintenance can be illustrated with the approximated water vapor budget: $P \sim -\nabla \cdot \mathbf{Q}$. The observed area-averaged ($P, -\nabla \cdot \mathbf{Q}$) of all 35 CSV(HRF³)s over their areas with $P \geq 45 \text{ mm day}^{-1}$ at their second peak intensity are shown in the bottom panel of Fig. 5d. Compared with ($P, -\nabla \cdot \mathbf{Q}$) of the observed CSV(HRF³)s, the averaged forecast errors for ($P, -\nabla \cdot \mathbf{Q}$) are slightly $\geq 25\%$. Clearly, forecasted

FIG. 3. Life cycle of the surface low coupled with the cold-surge flow involved with different stages of the CSV(HRF³) development into NWP explosive cyclones: 1) CSV(HRF³) formation (small blue circles), 2) second peak intensity of CSV(HRF³) (small red triangles), and 3) formation of an NWP explosive cyclone from the central Asian surface low (small green squares) without any linkage to CSV(HRF³) until the formation of the HRF³ event. NWP explosive cyclones developed from the three different types of surface lows are marked by larger blue circles, red triangles, and green squares, respectively.

CSV(HRF)s are drier than observed CSV(HRF³)s. Despite the $(P, -\nabla \cdot \mathbf{Q})$ reductions of GFS CSV(HRF³)s at their second peak intensity being less than observed, their signals in the forecasted development of CSV(HRF)s are not obscured by this hydrological weakening.

b. Relay forecast for occurrences of HRF events

After reaching second peak intensity, the time needed for the CSV(HRF)s to develop into a corresponding HRF³ event is shown in Fig. 6a. The preferred times needed by the second peak intensified CSV(HRF³) to form HRF³ events are 3 days (51%), 4 days (40%), and 5 days (9%). The optimum times for the formation of an HRF³ event from its parent CSV(HRF³)'s second peak intensity is also the time needed for the NP basin-scale circulation to develop an environment to facilitate the formation of an HRF event over the rainfall center around the SCS.

As can be seen from a comparison of occurrence times and intensities between the observation HRF³ events and the third peak intensity of the GFS CSV(HRF³) in Fig. 2, significant disparities emerge: 1) the GFS CSV(HRF³)'s third peak intensity forms/occurs earlier and 2) intensities are weaker than the observations. To properly use the GFS forecasts for the formation/occurrence of HRF³ events, the *relay forecast* procedure in Fig. 4 is adopted. Shown in Fig. 6a, the optimum time needed for the formation/occurrence of an of HRF³ event from its parent's CSV(HRF³) second peak intensity remains 3 days 6 h. Based on this optimum time, the relay GFS forecasts used to predict the formation/occurrence of HRF³ events are shown in Fig. 6b. Following the measurements for the forecast errors of the CSV(HRF³)'s second peak intensity, the forecast errors for 1) occurrence time, 2) intensity, 3) formation location, and 4) hydrological conditions for an HRF³ event/cyclone are presented.

FIG. 4. (a) Occurrence time of the CSV(HRF³) second peak intensity from the CSV(HRF³) formation time (abscissa) vs the CSV(HRF³) intensity measured with the $\zeta(925 \text{ hPa})$ averaged over the area of CSV(HRF³) with $\zeta(925 \text{ hPa}) \geq 1.8 \times 10^{-5} \text{ s}^{-1}$ (ordinate). The occurrence times t^o for the CSV(HRF³) second peak are denoted by red, blue, and green open circles for the occurrence time of the CSV(HRF³) second peak intensity on days 4, 5, and 6, respectively. (b) Illustration of the relay forecast for the second peak intensity of CSV(HRF³), based on the optimum time ($t_o = 3$ days 6 h) for the occurrence time of the CSV(HRF³) second peak intensity. If this occurrence time t^o is beyond the optimum time of occurrence, the relay forecast is performed from the time $t_r =$ observation time of occurrence t^o - optimum time t_o , as indicated by thin, long arrows.

1) OCCURRENCE TIME

For 35 GFS HRF³ events predicted by the relay GFS forecast approach (Fig. 6b) with the optimum time of 3 days 6 h ahead of their occurrences, the errors in occurrence times are zero (Fig. 7a).

2) INTENSITY

The third peak intensity is required by the occurrence of HRF³ events. To meet this requirement, 35 GFS HRF³ cyclones/events were identified (Fig. 2b). Their intensities

are within the range of $2.3\text{--}3.0 \times 10^{-5} \text{ s}^{-1}$, smaller than the corresponding observed HRF³ cyclones/events. With the relay GFS forecast approach with the optimum time (3 days 6 h) (Fig. 6b), 35 GFS HRF³ cyclones/events have an average value of $2.93 \times 10^{-5} \text{ s}^{-1}$, which is only 6% (Fig. 7b) smaller than observed.

3) LOCATION

The observed center location for 35 HRF³ cyclones (red crosses) and their parent CSV(HRF³) second peak intensities (red open triangle), as well as GFS forecast center locations for these HRF³ cyclones (blue crosses), are shown in the bottom panel of Fig. 7c. The forecast location errors for HRF³ cyclone centers are shown in the top panel with a clock representing the distance ratio and direction against the observed HRF³ cyclone centers. As in Fig. 5c, the outcome of error measurement is illustrated by two different approaches:

- Group I [HRF³(CV), HRF³(PM), HRF³(BM), HRF³(PS), and HRF³(BS)], where location errors are depicted by the ratio of the distance difference between the observed and forecasted trajectory distances from the locations of the parent CSV(HRF³)'s second peak intensity to those of the HRF³ cyclones/events, and the former trajectory distance.
- Group II [HRF³(BO) and HRF³(JV)], where these HRF³ cyclones and their parent CSV(HRF³)s are trapped in Borneo. The latter may not travel over too great of a distance to reach the former. Their location errors are essentially measured with the distance shown in the middle panel of Fig. 7c.

For group I, the distance errors of their trajectories are $\leq 10\%$, and the forecast HRF³ cyclone centers are primarily distributed north and east of the observed cyclone centers. For group II, the averaged distance error is 75 km.

4) HYDROLOGICAL CONDITIONS

Rainfall is a major concern during an HRF³ event. The area-averaged $(-\nabla \cdot \mathbf{Q})_{\text{HRF}^3}$ is $\sim 88\%$ of the area-average P_{HRF^3} over the HRF³ cyclone, about the same ratio between area-averaged P and $-\nabla \cdot \mathbf{Q}$ when CSV(HRF³)s reach their second peak intensity (section 3a). This 12% difference between P_{HRF^3} and $(-\nabla \cdot \mathbf{Q})_{\text{HRF}^3}$ (Fig. 8d, bottom) may consist of convergence of uncondensed water vapor flux, evaporation, and some computational error. Note that the GFS forecast errors of $[P_{\text{HRF}^3}, (-\nabla \cdot \mathbf{Q})_{\text{HRF}^3}]$ are $\geq 25\%$ of the observed $[P_{\text{HRF}^3}, (-\nabla \cdot \mathbf{Q})_{\text{HRF}^3}]$. The error may be attributed to the same factors causing the GFS forecast error of $(P, -\nabla \cdot \mathbf{Q})$ at the second peak intensity of CSV(HRF³).

FIG. 5. Bias of relay forecasts for the CSV(HRF³) peak intensity against the observations. Shown are errors for (a) occurrence time, (b) intensity [$\zeta(925 \text{ hPa})$], (c) location, and (d) hydrological condition ($P, -\nabla \cdot \mathbf{Q}$). The CSV(HRF³)s may be divided into two groups: propagating and trapped. The former group includes CSV(HRF³) CV, CSV(HRF³) PM, CSV(HRF³) BM, CSV(HRF³) PS, and CSV(HRF³) BS, while the latter group consists of CSV(HRF³) BO and CSV(HRF³) JV. The location errors for the first group are measured with the ratio of the distance difference between the forecasted and observed trajectories for CSV(HRF³)s, the distance of the latter trajectories, and the direction of the forecasted CSV(HRF³) location compared to the observed. The second group of CSV(HRF³)s is trapped within Borneo and the location error is only measured with the distance differences between the forecasted and observed trajectories of CSV(HRF³)s. Errors for the GFS(HRF³) hydrological condition are measured with a ratio of the difference for ($P, -\nabla \cdot \mathbf{Q}$) averaged over the area of CSV(HRF³) with ($P, -\nabla \cdot \mathbf{Q}$) $\geq 45 \text{ mm day}^{-1}$ between the forecast and the observations.

FIG. 6. As in Fig. 4, but for the relay forecasts of the third peak intensity of CSV(HRF³) formation/occurrence of HRF³ cyclone/event. The occurrence times of a HRF³ event within and beyond the optimum time of 3 days 6 h are colored red and blue, respectively.

The occurrence of an HRF³ event also needs to meet the following two criteria:

- 1) Occurrence synchronization of the NWP explosive cyclone and HRF event/cyclone

On the occurrence dates of 35 identified HRF³ events, 35 NWP explosive cyclones are also identified. The observed surface pressure tendency Δp_s^o for these 35 explosive cyclones is shown in Fig. 8a; Sanders and Gyakum's (1980) criterion $\Delta p_s^o \leq -24 \text{ hPa day}^{-1}$ is marked by a dashed line. All 35 identified explosive cyclones meet this criterion. The scatter diagram of occurrence dates for the HRF³ events around the SCS (ordinate) versus occurrence dates of NWP explosive cyclones (abscissa) shows results that are distributed along the *diagonal* between these two axes. Apparently, occurrences of these HRF³ events and the NWP explosive cyclone synchronize.

Using the optimum time ($t_o = 3 \text{ days } 6 \text{ h}$) to perform the relay forecasts for the formation of HRF³ events after the second peak intensity of their

corresponding parent CSV(HRF³)s, the Δp_s^f values of the GFS explosive cyclones that correspond to the GFS HRF³ events are shown in Fig. 8c. Chen et al.'s (2012) criterion for the Δp_s^f forecasted value of the GFS explosive cyclone is $\leq -15 \text{ hPa day}^{-1}$ and is marked by a dashed line. The scatter diagram for the occurrence date of GFS HRF³ events versus the occurrence date of GFS NWP explosive cyclones shows results that are distributed along the diagonal as observed (Fig. 8b). The occurrence of the GFS NWP explosive cyclone and the GFS HRF³ events synchronize.

- 2) Simultaneous occurrences of maximum intensities in three weather systems: HRF cyclone/event, NP subtropical anticyclone, and NWP explosive cyclone

Following Chen et al.'s (2012) approach, shown in Figs. 9a–c are time series (blue lines) for the maximum westerlies at the formation longitude of an HRF event u_{HRF}^o (850 hPa), and the maximum 850-hPa tropical trade easterlies of the NP subtropical anticyclone u_{TTE}^o (850 hPa) and the maximum 850-hPa westerlies at the formation longitude of an NWP explosive cyclone u_{PEC}^o (850 hPa). The composite time series for u_{HRF}^o (850 hPa), u_{TTE}^o (850 hPa), and u_{PEC}^o (850 hPa) are denoted by thick red lines superimposed on the corresponding time series in Figs. 9a–c, respectively. It is clear that the HRF³ event is *formed* when simultaneous occurrences of maximum intensities of u_{PEC}^o (850 hPa), u_{TTE}^o (850 hPa), and u_{HRF}^o (850 hPa) occur on day 0.

The requirement for the simultaneous occurrence of maximum intensities in three weather systems with the GFS forecasts is shown in Figs. 9d–f. The GFS forecasts for 35 HRF³ events in Fig. 9 are used to prepared the time series for u_{PEC}^f (850 hPa), u_{TTE}^f (850 hPa), and u_{HRF}^f (850 hPa). However, the data used to construct the time series ahead of the forecasts are gathered from observations. Despite the bias in the GFS *relay forecasts* with the optimum time of 3 days 6 h shown in Fig. 7, the simultaneous occurrence requirement of maximum intensity in the three weather systems (HRF³ cyclone/event, NP subtropical anticyclones, and NWP explosive cyclone) are well met by the GFS relay forecasts.

4. Forecast advisory

The life cycle of an HRF³ event from the formation of its parent CSV(HRF³) to the occurrence of the HRF³ event varies from 6 to 10 days (Fig. 1). Regional weather services, such as the Malaysia Meteorological Department (Maisarah et al. 2013), the Vietnam National Hydrometeorological Service (UNISDR 2013), and the

FIG. 7. As in Fig. 5, but for relay forecasts of the third peak intensity of CSV(HRF³) formation of occurrence of an HRF³ cyclone/event.

Meteorological Research Institute of JMA (Saito et al. 2012) use different regional forecast models and their products to predict HRF events. These endeavors often have less than satisfactory outcomes even with short-range forecasts for HRF events. The NCEP GFS provides a 16-day global forecast outlook (NWS/EMC 2016), but accurate forecasts for CSV(HRF³)s with a long life cycle are still beyond the reach of state-of-the-art numerical weather prediction techniques. As shown by the GFS forecast compared with observations presented in section 3, the optimum forecast time for both the second peak

intensity of CSV(HRF³)s from its formation and the formation/occurrence of HRF³ events from the second peak intensity of their parents CSV(HRF³)s is about 3 days 6 h. This time assessment is based on there being zero error in the occurrence time, error $\leq 10\%$ in intensity and location, and error $> 25\%$ in $[P, (-\nabla \cdot Q)]$ of CSV(HRF³)s at their second peak intensity and during the formation of HRF³ events. As summarized in the flowchart in Fig. 10, these findings allow us to introduce a forecast advisory with the *relay forecast approach* to predict the development of CSV(HRF³)s over their entire life cycles.

FIG. 8. (a) Surface pressure tendency Δp_s^o of observed NWP explosive cyclones related to HRF³ events. (b) The scatter diagram for the occurrence date of an observed NWP explosive cyclone (ordinate) vs the occurrence date of an observed HRF³ event (abscissa). (c),(d) As in (a),(b), respectively, but for GFS relay forecasts of the corresponding observed NWP explosive cyclone and HRF³ event.

a. Illustration of forecast advisory

Through multiple interactions with the sequential cold-surge flows in the SCS, the development of CSV(HRF³)s over their life cycles is characterized by three major processes: CSV(HRF³) formation, the second peak intensity, and the formation/occurrence of HRF events. The latter process is coupled with two special requirements: 1) occurrence synchronization of an HRF event and an NWP explosive cyclone and 2) the simultaneous occurrence of the maximum zonal winds in three weather systems over the NP basin: (i) the maximum westerlies of an HRF³ cyclone, (ii) the maximum tropical trade easterlies, and (iii) the maximum westerlies of an NWP explosive cyclone. Figure 10 illustrates a four-step forecast advisory developed from the multiple interactions of CSV(HRF³) with the SCS cold-surge flows.

1) STEP 1: IDENTIFICATION OF CSV IN THE VICINITY OF THE PHILIPPINES AND BORNEO

Prepared with GFS initial analyses as described in section 2, the 925-hPa streamline chart superimposed with TRMM rainfall/Geostationary Meteorological Satellite (GMS) or Multifunctional Transport Satellite (MTSAT; Meteorological Services Centre Japan 1997) cloud images are utilized to identify the CSV formation around the Philippines and Borneo. The daily surface analysis charts issued by weather services (JMA, TMD,

BOM, and NCEP SRRS around the SCS) are applied to verify the identified CSV. Two types of CSVs are identified: *Philippines* and *Borneo*. The former is formed around 0600 UTC over the vicinity of the Philippines, while the latter is formed around 0000 UTC in Borneo.

2) STEP 2: IDENTIFICATION OF CSV(HRF³) USING THE GFS FORECASTS FOR THE CSV(HRF³) SECOND PEAK INTENSITY AND THE SURFACE LOW COUPLED WITH THE COLD-SURGE FLOW RELATED TO THE CSV(HRF³) DEVELOPMENT

The evolution of CSV(HRF³) undergoes an intensification while reaching its second peak intensity before it develops into an HRF³ event. Although the time window for the development to gain this peak intensity is about 3–5 days (section 3), the optimum time is 3 days 6 h. This evolutionary feature of CSV(HRF³) provides a feasible way to separate it from non-developing CSVs. Following the procedure presented in section 3, the area-averaged ζ (925 hPa) time series of the GFS forecast for an identified CSV during the first 6 days is used to examine whether the second peak intensity of this CSV appears with the area-averaged ζ (925 hPa) value $\geq 90\%$ of the mean second peak intensity of observed CSV(HRF³) shown in Fig. 5b. If the time for a GFS CSV(HRF³) to reach its second peak intensity is beyond the optimum time, the GFS forecast will be delayed to the time 3 days 6 h ahead of the

FIG. 9. Time series for $u(850\text{ hPa})$ at locations of the maximum 850-hPa zonal winds of three weather systems of interest: (a) $u_{\text{HRF}}^o(850\text{ hPa})$, (b) $u_{\text{TTE}}^o(850\text{ hPa})$, and (c) $u_{\text{PEC}}^o(850\text{ hPa})$, related to the formation/occurrence of 35 HRF³ events. These observational $u(850\text{ hPa})$ time series are depicted by thin lines with colors corresponding to the HRF events shown in Fig. 6a. A thick red line in (a)–(c) exhibits the mean time series for 35 HRF³ events. Time series for GFS (d) $u_{\text{HRF}}^f(850\text{ hPa})$, (e) $u_{\text{TTE}}^f(850\text{ hPa})$, and (f) $u_{\text{PEC}}^f(850\text{ hPa})$, as in (a)–(c), for relay forecasts of HRF³ events from the second peak intensities of 35 CSV(HRF³s). Results are presented by different colors corresponding to the delay time shown in Fig. 6b. The mean time series for 35 HRF events are displayed by the thick dark-blue lines in (d)–(f).

FIG. 10. Flowchart of the forecast advisory for the cold-season HRF³ events developed from multiple interactions with the cold-surge flows in the SCS that occurred over the rainfall centers around the region.

occurrence time for this CSV(HRF³) second peak intensity, as shown in Fig. 4. The forecast approach presented here serves three purposes:

- (i) to separate CSV(HRF³)s from the large number of CSVs identified in step 1;
- (ii) to gain a more accurate forecast time for the occurrence of the CSV(HRF³) second peak intensity, and
- (iii) to track whether the surface low systems coupled with the cold-surge flow linked to either the formation or second peak intensity of CSV(HRF³) may develop into an NWP explosive cyclone synchronized with the occurrence of an HRF³ event.

3) STEP 3: OCCURRENCE SYNCHRONIZATION OF THE SOUTHEAST ASIAN HRF³ EVENT AROUND THE SCS AND THE NWP EXPLOSIVE CYCLONE

The optimum time for a great majority of CSV(HRF³)s (72/83 ~ 87%) to form HRF³ events from their second peak intensity is from about 3 days 6 h to 4 days 6 h, and for some minority of the CSV(HRF³)s (~8%), the time is beyond 4 days 6 h. Thus, the GFS forecast issued at the time a CSV(HRF³) reaches its second peak intensity for the next several days is used to determine how the *relay forecast should proceed* for the formation/occurrence of HRF³ events. Assume the GFS CSV(HRF³) third peak intensity appears at the optimum time of 3 days 6 h, *three necessary procedures* should be pursued:

- (i) We construct the time series of area-averaged $\zeta(925 \text{ hPa})$ for the identified CSV(HRF³) from its

formation to the formation/occurrence of the corresponding HRF³ event. If the third peak intensity of a CSV(HRF³)/HRF cyclone is larger than 1.2σ of the detrended $\zeta(925 \text{ hPa})$ time series, the HRF³ events *should* form/occur.

- (ii) We confirm the occurrence/formation of the GFS NWP explosive cyclone (the deepening rate of this GFS cyclone $\leq -15 \text{ hPa day}^{-1}$), as required by the occurrence synchronization of the GFS HRF³ event and the GFS NWP explosive cyclone.
- (iii) If the *third* peak intensity of GFS CSV(HRF³) does not appear by the optimum time of 3 days 6 h, it may appear beyond this optimum time. In this case, the third peak intensity for CSV(HRF³) may not reach all required criteria by formation/occurrence of an HRF³ event. As illustrated in Fig. 6, the relay forecast every 6 h by the GFS will be checked until all required criteria are met within the optimum occurrence/formation time for a GFS HRF³ event in 3 days 6 h. Then, the forecast for the formation/occurrence of GFS HRF³ can be confirmed.

4) STEP 4: SIMULTANEOUS OCCURRENCE OF MAXIMUM INTENSITY IN THE HRF CYCLONE, THE NP ANTICYCLONE, AND THE NWP EXPLOSIVE CYCLONE

The midlatitude–tropical interaction happens not only through the northeast Asian cold-surge flow, but also the basin-scale interactions between the HRF³ cyclone and the NWP explosive cyclone through the NP subtropical anticyclone. The latter interaction is

realized by the occurrence simultaneity among the maximum westerlies of the HRF³ cyclone/event, the maximum tropical trade easterlies of the North Pacific anticyclone, and the maximum 850-hPa westerlies of the NWP explosive cyclone. The forecast for the formation/occurrence of GFS HRF³ is further confirmed by this requirement and can be issued in an operational setting.

b. Feasibility test of the forecast advisory

1) NECESSARY REQUIREMENTS

(i) CSV identification

Based on the identification approach presented in section 2, 51 CSVs are identified over three cold seasons (2013–15); 6 of these 51 CSVs are CSV(HRF³)s. Additionally, one CSV developed into a central Vietnam HRF² event and two CSVs evolved into Borneo HRF² events through *two* peak intensities. However, these three CSVs were not the main concern for the current study. The temporal evaluations of 45 CSVs depicted by the GFS forecasts are marked by small black dots in Fig. 11a. They are used as reference to contrast with evaluations of six GFS CSV(HRF³)s marked with red crosses.

(ii) CSV(HRF³) identification and surface low tracking through the intensification of its second peak intensity

The evolution of six CSV(HRF³)s is depicted with the relay forecasts of GFS shown in Figs. 11b and 11c. The second peak intensity for these six CSV(HRF³)s is denoted by open circles in Figs. 11a and 11b, while the formation/occurrence for six corresponding HRF³ events is marked by open triangles in Figs. 11a and 11c.

The population ratio between CSVs and CSV(HRF³)s is 45:6. Therefore, it may *not* be feasible to track the development for every CSV. A practical, operational approach should be developed to identify the formation of CSV(HRF³)s. A third-order polynomial regression line (red) is added to indicate the CSV(HRF³) development in Fig. 11a. The second peak intensity for CSV(HRF³)s marked by open circles is notable from the GFS forecasts. The observation third peak intensities for all six CSV(HRF³)s are also presented by solid triangles to verify the GFS relay forecasts. No error is shown in the occurrence time for the CSV(HRF³) second peak intensity (Fig. 12a), but errors in intensity (Fig. 12b), location (Fig. 12c), and hydrological conditions (P , $-\nabla \cdot \mathbf{Q}$) are within the threshold values of the variables considered, as shown in Fig. 5. The successful GFS

forecasts for the six CSV(HRF³) second peak intensities offer a feasible way to identify CSV(HRF³)s.

Following step 2 of the forecast advisory, three northeast Asian surface lows, coupled with the cold-surge flows linked to three CSV(HRF³) second peak intensities, developed into NWP explosive cyclones. The occurrence of these explosive cyclones synchronizes with the three HRF³ events.

2) SUFFICIENT REQUIREMENTS

The following two sufficient requirements must be met to confirm the formation/occurrence of HRF³ events.

(i) Occurrence synchronization of an HRF³ cyclone/event and an NWP explosive cyclone

The deepening rate of six observational explosive cyclones corresponding to the six GFS HRF³ cyclones/events is $\leq -24 \text{ hPa day}^{-1}$ (not shown). In contrast, the six GFS NWP explosive cyclones corresponding to six GFS HRF³ cyclones/events exhibit their deepening rates of surface pressure Δp_s^F around $\leq -15 \text{ hPa day}^{-1}$ (Fig. 13a). The occurrence synchronization dates of six GFS HRF cyclones/events and the six GFS NWP explosive cyclones are shown by a diagonal in the scatter diagram for the occurrence dates of the former (ordinate) versus those of the latter (abscissas) shown in Fig. 13b. This sufficient requirement is met by these six GFS HRF cyclones/events.

(ii) Occurrence simultaneity of maximum intensities in three weather systems (HRF³ cyclone/event, tropical trade easterlies during an NP subtropical anticyclone, and NWP explosive cyclone)

In Fig. 9, the maximum intensities for the three weather systems are depicted by u_{HRF}^F , u_{TTE}^F , and u_{PEC}^F at 850 hPa. The six cases for CSV(HRF³) over the 2013–16 period used to verify this forecast advisory belong to two groups:

- 1) three CSV(HRF³)s reached their second peak intensity following their formation in 3 days 6 h and another three CSV(HRF³)s formed in 4 days 6, while
- 2) four CSV(HRF³)s needed 3 days 6 h from their second peak intensity to form their HRF³ cyclones/events and while another two CSV(HRF³)s took 4 days 6 h.

The time series for u_{HRF}^F (850 hPa) at the location for this HRF³ cyclone center 5 days prior to and 5 days after the occurrence of HRF³ events for all six cases with the occurrence date of day 0 are shown in Fig. 13c. The forecast time series for u_{HRF}^F (850 hPa) included u_{HRF}^0 (850 hPa) before the formation of their parent CSV(HRF³)s. Note that if the GFS formation time for an HRF³ cyclone/event from its parent CSV(HRF³)

FIG. 11. (a) Temporal evolution of six CSV(HRF³)s (red crosses) measured with the area-averaged $\zeta(925 \text{ hPa})$ with a threshold value $\geq 1.8 \times 10^{-5} \text{ s}^{-1}$ for the three cold seasons of 2013–16 through *two* steps of relay forecasts for the second peak intensity denoted by open circles and for the formation/occurrence of HRF³ events marked by open triangles. To validate these two steps of the relay GFS forecasts, six occurrences of observed CSV(HRF³) second peak intensity and six HRF³ events are shown by six large dots and six solid triangles, respectively. The relay forecasts of HRF³ events (open triangles) are connected with observed CSV(HRF³) second peak intensities of six parent CSV(HRF³)s by thin lines. A third-order polynomial regression line is also added onto the temporal evolutions of six CSV(HRF³)s to show the mean CSV(HRF³) time series and a strip of one standard deviation of CSV(HRF³) distribution. The temporal evolution of 45 CSVs identified with GFS initial analyses until their demise/disappearance from the GFS forecasts, the third-order polynomial regression line of forecast CSVs, and a standard deviation (light blue strip) with respect to this time series are added on the bottom part of (a) to contrast with (b) the temporal evolutions of GFS CSV(HRF³) through their relay forecasts for the second peak intensity of GFS HRF³ and (c) for the formation/occurrence of GFS HRF³ events.

FIG. 12. Bias of relay forecasts for six CSV(HRF³) second peak intensities against observations: errors in (a) occurrence time, (b) intensity [$\zeta(925 \text{ hPa})$], (c) location, and (d) hydrological condition ($P, -\nabla \cdot \mathbf{Q}$). (e)–(h) As in (a)–(d), but for the bias in the relay forecasts for six HRF³ events from their second peak intensities. A yellow strip of 1.2σ (σ shows a standard deviation with respect to the averaged error) for every variable considered is added onto its averaged error.

from its second peak intensity is larger than 3 days 6 h, this extra time is used to delay the GFS forecast for an additional 3 days 6 h. The same procedure is utilized to prepare the time series for $u_{\text{TTE}}^F(850 \text{ hPa})$ (Fig. 13d) and $u_{\text{PEC}}^F(850 \text{ hPa})$ (Fig. 13e) at the longitude of

the NWP explosive cyclone center. The occurrence simultaneity of the maximum intensities in an HRF³ cyclone/event, the tropical trade easterlies, and the NWP explosive cyclone is also met by the six GFS HRF events.

FIG. 13. (a) Surface pressure tendency Δp_s^F of GFS NWP explosive cyclone linked to HRF³ events. (b) Scatter diagram for occurrence date of GFS NWP explosive cyclones (ordinate) vs occurrence date of GFS HRF³ events (abscissa). Time series for $u(850\text{ hPa})$ at locations of the maximum 850-hPa zonal winds of three weather systems considered: (c) $u_{HRF}^F(850\text{ hPa})$, (d) $u_{TTE}^F(850\text{ hPa})$, and (e) $u_{PEC}^F(850\text{ hPa})$, related to the formation/occurrence of six HRF³ events. These GFS $u(850\text{ hPa})$ time series are depicted by thin blue lines for relay forecasts of four HRF³ events from their second peak intensities and thin red lines for relay forecast of two HRF³ events with a 1-day delay from their second peak intensities. The thick blue (red) line depicts the mean time series for the first (second) group of GFS HRF³ events.

Both necessary and sufficient requirements are satisfied by six GFS HRF³ events. In addition, despite under-forecasted intensities for six GFS HRF³ cyclones (Fig. 11a), errors in their occurrence timing (Fig. 12a) are zero, and errors in their intensity (Fig. 12f), location

(Fig. 12g), and hydrological conditions (Fig. 12h) are all within the threshold values shown in Fig. 7. In conclusion, the proposed forecast advisory works for the formation/occurrence of HRF³ events from their parent CSV(HRF³)s over all the cold-season rainfall centers around the SCS.

5. Concluding remarks

The development of CSV(HRF)s from their formation into the formation of HRF events can be classified by the occurrence frequency of their peak intensity *doubled* or *tripled* over their life cycles through interactions with cold-surge flows in the SCS. These events are denoted as HRF² and HRF³ events, respectively. The CSV(HRF²) life cycle necessary to form the HRF² event is ≤ 5 days, but to form the HRF³ events the length of time is ≥ 6 days. The NCEP GFS global forecast outlooks were used to forecast the formation of HRF² events with the addition of a forecast advisory introduced by Chen et al. (2012) for central Vietnam. Nevertheless, occurrence forecasts for HRF³ events in terms of the GFS after 6 days are still beyond our reach. Chen et al. (2015b) found the CSV(HRF³) development to form HRF³ undergoes triple peak intensities. Making good use of the CSV(HRF³) second peak intensity to forecast the formation/occurrence of HRF³, a forecast advisory was developed with the relay forecast approach for the formation/occurrence of HRF³ events over the entire SCS.

Assessing in terms of the zero-error criteria for the occurrence time of CSV(HRF³) second peak intensity, the optimum forecast time is about 3 days 6 h (Fig. 4). Based on this special characteristic of CSV(HRF³), a *four-step* forecast advisory was developed in this study:

- 1) Step 1—CSVs are identified with the streamline charts prepared with the GFS initial analysis superimposed by T_{BB} images or rainfall, supplemented with surface analysis maps issued by weather services of countries located throughout the SCS.
- 2) Step 2—on average, slightly more than 17 CSVs originate in the vicinity of the Philippines and Borneo during the cold season (October–February). In contrast, the occurrence frequency for CSV(HRF³) is ~ 2.3 . Based on the occurrence optimum time of the CSV(HRF³) second peak intensity from the formation of its parent CSV(HRF³), the GFS forecast can be used to identify the occurrence of the CSV(HRF³) second peak intensity. This special feature of CSV(HRF³)s is used to separate CSV(HRF³)s from the majority of the CSV population.
- 3) Step 3: using GFS forecasts, the optimum forecast time for the formation/occurrence of HRF³ events from its second peak intensity is also 3 days 6 h. If this second peak intensity occurs within this optimum time, the GFS forecast at this occurrence time is used to forecast the formation/occurrence of an HRF³ event. If the GFS forecast of the CSV(HRF³)

second peak intensity occurs beyond this optimum time, application of the GFS forecast for the HRF³ formation/occurrence is delayed until the occurrence time for this CSV(HRF³) second peak intensity is 3 days 6 h ahead of the HRF³ occurrence formation.

- 4) Step 4—the formation/occurrence of an HRF³ event is warranted by satisfying two sufficient requirements: 1) occurrence synchronization of HRF³ events and an NWP explosive cyclone and 2) simultaneous occurrence of the maximum u_{HRF}^F (850 hPa), u_{TTE}^F (850 hPa), and u_{PEC}^F (850 hPa).

The GFS initial analyses and forecasts for three seasons (2013–16) are utilized to perform the verification test of the proposed forecast advisory for the formation/occurrence of HRF³ events over the cold-season rainfall centers around the SCS.

1) Necessary requirements

Following step 1, 51 CSVs are identified using the GFS initial analyses. The average population of CSVs during the three cold seasons is about 17 CSVs per season, close to the long-term-averaged CSV population (~ 17.2 CSVs per season). Using the GFS forecasts, six CSV(HRF³)s are identified, as required by step 2. Three exhibit their second peak intensity at 3 days 6 h after their parent CSV(HRF³)s form, but another three form at 4 days 6 h. Thus, three CSV(HRF³)s are confirmed by the 1-day delay of GFS forecasts.

2) Sufficient requirements

The relay GFS forecasts from the occurrence time of the CSV(HRF³) second peak intensity show that HRF³ events develop from four CSV(HRF³)s within 3 days 6 h, but the other two CSV(HRF³)s need an additional day. The formation forecasts of their HRF³ events are delayed by 1 day. Results from the GFS forecasts show that the occurrence time errors for six HRF³ events are zero, errors for intensity and location are $\leq 10\%$, and errors for hydrological conditions are $\sim 25\%$. These errors are within the error threshold values for 35 GFS HRF³ events. The GFS forecasts for six HRF³ events also satisfy both sufficient requirements.

The verification test presented in section 4b shows that the proposed forecast advisory for the HRF³ events around the SCS is feasible.

The HRF² and HRF³ events can be separated by the development times from their parent cold-surge vortices. Using some characteristic differences between CSVs and CSV(HRF²)s, the in-phase occurrence of three monsoon (30–60, 10–20, and 5 day) modes in rainfall and wind speed at the formation/occurrence

TABLE A1. Explanations of key acronyms used in this study.

Acronym	Definition/expansion
HRF	Heavy rainfall/flood
CSV	Cold-surge vortex does not develop into a heavy rainfall/flood event
CSV(HRF)	Cold-surge vortex develops into a heavy rainfall/flood event
CSV(HRF ²)	CSV(HRF) exhibits peak intensity twice between formation and occurrence of an HRF event
CSV(HRF ³)	CSV(HRF) exhibits peak intensity three times between formation and occurrence of an HRF event
CSV(HRF ⁿ)AB	CSV(HRF ⁿ) forms in area A and moves to area B where it develops into a heavy rainfall/flood event
	Formation area of CSV(HRF ⁿ) ~ nce area of an HRF ⁿ event
CV	Philippines and surrounding vicinity Vietnam
PM	Philippines and surrounding vicinity Malay Peninsula
BM	Borneo Malay Peninsula
PS	Philippines and surrounding vicinity Sumatra
BS	Borneo Sumatra
BO	Borneo Borneo
JV	Borneo Java
HRF ²	HRF event occurred at the time of the CSV(HRF ²)'s second intensity peak
HRF ³	HRF event occurred at the time of the CSV(HRF ³)'s third intensity peak
HRF ⁿ (AB)	As explanation of CSV(HRF ⁿ)AB, A is the formation area of its parent CSV(HRF ⁿ), while B is the occurrence area of an HRF ⁿ event
NCEP	National Centers for Environmental Prediction
GFS	Global Forecast System
NWP	Northwest Pacific
NP	North Pacific
$\Delta p_s^o(\Delta p_s^F)$	Observed (forecasted) surface pressure tendency
$u_{\text{HRF}}^o(u_{\text{HRF}}^F)$	Observed (forecasted) max westerlies of an HRF cyclone/event
$u_{\text{TTE}}^o(u_{\text{TTE}}^F)$	Observed (forecasted) max tropical trade easterlies
$u_{\text{PEC}}^o(u_{\text{PEC}}^F)$	Observed (forecasted) max westerlies of an NWP explosive cyclone

time of an HRF event, the occurrence synchronization of an HRF cyclone/event and NWP explosive cyclone, and the simultaneity occurrence of maximum u_{HRF}^F , u_{TTE}^F , and u_{PEC}^F , Chen et al. (2012) introduced a forecast advisory for the formation/occurrence of HRF² events in central Vietnam. In the present study, a forecast advisory for the formation/occurrence of HRF³ events is developed from the utilization of the relay GFS forecasts for the occurrence of the CSV(HRF³) second peak intensity and the relay GFS forecasts for the formation/occurrence of HRF³ events from the second peak intensity of their parent CSV(HRF³)s. After the development/formation mechanisms for both HRF² and HRF³ events around the SCS were disclosed by Chen et al. (2015a,b), forecasts for the occurrences of both HRF² and HRF³ events around the SCS with the NCEP GFS forecasts can be feasibly performed with the combination of both forecast advisories by Chen et al. (2012) and this present study.

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APPENDIX

Explanation of Key Acronyms Used in This Study

The acronyms used in this study are explained in Table A1.

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