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Synoptic Conditions and Potential Causes of the Extreme Heavy Rainfall Event of January 2009 Over Mindanao Island, Philippines

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ORIGINAL PAPER

Synoptic conditions and potential causes of the extreme heavy rainfall event of January 2009 over Mindanao Island, Philippines

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Abstract

This study investigates the synoptic conditions that led to the heavy rainfall/flood (HRF) event in Mindanao Island, Philippines (122−127°E; 5−10°N), on January 2009 (JAN2009 HRF) that are less emphasized in previous works. Extensive flooding was reported over Cagayan de Oro City in the northern part of Mindanao, where the rainfall on January 10, 11, and 13, 2009, exceeded the 99th percentile of daily rainfall records of all January of the city from 1979 to 2017 by almost two times. A similar exceedance was also felt in Hinatuan station over the eastern coast of Mindanao Island on January 15, 2009. The interaction of a cold surge shearline over the northern Mindanao Island and the warm tropical easterlies led to enhanced moisture convergence. The warmer air mass is forced to ascend by the advancing colder air mass because it has lower density than the colder air mass. The enhanced moisture convergence and buoyancy difference by the air masses led to enhanced ascent and consequently rainfall along the cold surge shearline. Further analysis shows that enhanced anomalous easterly and northerly winds at 925 hPa are apparent over the Philippines. The anomalous easterly winds sustained the supply of warmer easterlies and collaboratively interacted with the northerly winds that supplied colder temperature air mass. The climatology of this HRF event was examined for all January from 1979 to 2017. The authors identified 15 other cases that are similar to the JAN2009 HRF event and performed lag composite analyses. The results show that the occurrence of these HRF events is facilitated by the southward expansion of the high-pressure system to the north of the Philippines, enhanced cold and warm temperature advections, and enhanced moisture convergence along the cold surge shearline. The results of this study have important implications for disaster mitigation during the northeast monsoon season when rainfall activities are, in general, less intensive over this region.

Keywords Philippines · Mindanao Island · Tail end of a cold front · Cold surge shearlines · Heavy rainfall

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1 Introduction

Located over the western rim of the Pacific Ocean, the Philippines is vulnerable to extreme weather events such as floods and droughts. Tropical cyclones (TCs) are one of the synoptic-scale systems that induce extreme heavy rainfall/flood (HRF) events in the country (Cayanan et al. 2011; Cruz and Narisma 2016; Kubota et al. 2017). On average, 20 TCs enter the Philippine Area of Responsibility (PAR) per year, nine of which makes landfall (Cinco et al. 2016). Sometimes, these TCs may interact with the prevailing southwest monsoon (Cayanan et al. 2011) that further enhances the rainfall over the western coast of the country or induces the early onset of the southwest monsoon season (Kubota et al. 2017). On the other hand, prolonged droughts over the country are linked to El Niño conditions, the warm phase of the El Niño-Southern Oscillation (e.g., Porio et al. 2019). For example, many parts of the country experienced less rainfall from January to May during the 1997/1998 strong El Niño (see Figure 12 of Porio et al. 2019). These extreme weather events can have devastating socioeconomic impacts. It is therefore necessary to examine the mechanisms of the different systems inducing these extreme weather events.

According to Chen et al. (2015a, b), the HRF events in some parts of Southeast Asia such as Malaysia, Vietnam, and the Philippines often occur when easterly waves interact with the East Asian cold surge vortex. Its impact is manifested by seasonal variation of the rainfall climatology over the countries in Southeast Asia, particularly those that are on both sides of the South China Sea. A pilot study called the Winter Monsoon Experiment (MONEX) on December 1974 examined the possible interaction between the northeasterly cold surges off the Asian continent and the convective disturbances in the near equatorial region. Chang et al. (1979) found that following the cold surge, the freshening of low-level northeasterlies spreads rapidly (within 12–24 h) from the Taiwan and Luzon Straits southwestward to near 16°N and then down to the near equatorial latitudes with almost no time lag. The southward intrusion of cold temperatures, however, is concentrated in the western part of the South China Sea along the Vietnam coast and progresses slowly southward. As a result, these two developments experience widely spread increased northeasterly monsoon winds prior to the cold temperature establishment. Yokoi and Matsumoto (2008) examined the synoptic-scale atmospheric conditions over the South China Sea that caused the heavy rainfall in central Vietnam in November 1999. On November 2–3, 1999, large amounts of precipitation exceeding 600 mm in two days were recorded in Central Vietnam. It was found that the collaborative effects of an enhanced cold surge and the presence of a tropical depression-type disturbance in southern Vietnam induced this HRF event. In mid-December 2006 to late January 2007, the worst flood of the century happened in the southern Peninsular Malaysia and was caused by three extreme precipitation episodes. These extreme precipitation events were mainly associated with the occurrence of three dominant factors: the strong northeast cold surge; the absence of the Borneo vortex; and the influence of the eastward propagating Madden–Julian Oscillation (MJO) disturbances. The interactions among these systems greatly determine the variability of the organized convection, especially over the western part of the region (Tangang et al. 2008). In late February 2008, the eastern coast of the Philippines experienced an HRF event due to enhanced cold surge activity (Pullen et al. 2015). Pullen et al. (2015) found that this HRF event coincided with an active MJO over the maritime continent and that the La Niña condition over the western North Pacific was favorable for the enhancement of rainfall.

On January 2009, some parts of Mindanao Island, the southern region of the Philippines, experienced heavy rainfall events resulting in extensive flooding (hereafter, JAN2009 HRF)

(Faustino-Eslava et al. 2011; Yumul et al. 2013). This HRF event has been associated with the cold surge shearline or locally referred to as the "Tail end of a cold front." Faustino-Eslava et al. (2011) noted that some of the weather stations by the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA), the country's official weather bureau, exceeded the climatological monthly normal rainfall by about 160% from January 1 to 18, 2009 (see their Figure 4). This event is further discussed in Sect. 3.

The cold surge shearline is formed by the interaction of the trailing end of an eastward propagating cold front over the north Pacific and the warm easterly winds from the equatorial region (e.g., Olaguera et al. 2021). Enhanced convergence is apparent along the cold surge shearline since warm winds are forced to ascend in the troposphere. Olaguera et al. (2021) examined an HRF event that occurred on January 2017 (JAN2017 HRF) over Mindanao Island. Excessive rainfall from 00 UTC January 16 to 00 UTC January 17, 2017, led to urban flooding over Cagayan de Oro City in the northern part of Mindanao Island. They further noted that the presence of a westward propagating low-pressure area over Mindanao Island further enhanced the interaction between the warm easterlies over the tropical region and cold northeasterlies. The impact of cold surge shearlines is also observed during pre-summer (e.g., Olaguera and Matsumoto 2020) where it contributes to the pre-summer monsoon rainfall of the northern Philippines. Based on these aforementioned studies, it is recognized that the cold surge shearline is another synoptic-scale system that induces HRF events over the country especially during the northeast monsoon season.

In this study, we addressed the following issues:

(a) The studies by Faustino-Eslava et al. (2011) and Yumul et al. (2013) focused only on the impact of the JAN2009 HRF event and no detailed meteorological analysis were performed. Although this event has been attributed to the effect of the cold surge shearline, it is not clear how this synoptic system induced this HRF event.

(b) Mindanao Island is an important agricultural region in the southern Philippines (Philippine Statistics Authority, 2019) and appears to experience HRF events that are not associated with TCs more frequently during the northeast monsoon season (i.e., from December to March). In fact, Olaguera et al. (2021) identified 34 of such cases, in which 25 cases occurred over Mindanao Island alone. Unlike their study, however, the JAN2009 HRF event lasted for several days and there was no clear low-pressure area (i.e., cyclonic circulation) that was located over Mindanao Island. Hence, the mechanisms that induced the JAN2009 HRF might be different from the JAN2017 HRF case that they examined.

The objective of this study is, therefore, to examine the JAN2009 HRF event in detail including the mechanisms leading to this extreme weather event that is less emphasized in previous works. The rest of the paper is organized as follows. Section 2 presents the different data sources and methodology used in this study. A description of the JAN2009 HRF event is presented in Sect. 3 including the potential causes that induced it. Summary and discussions are presented in Sect. 4.

2 Data and methodology

2.1 Data

This study utilized the following data sets:

a. Daily rainfall data from the synoptic stations of PAGASA from 1979 to 2017 for Lumbia Airport, Butuan City, Hinatuan, and Surigao City stations. These stations are shown in Fig. 1. The data at Lumbia Airport are only available until 2013 because the weather station here was transferred to a nearby location (Laguindingan Airport), and these stations are both located in Cagayan de Oro City. The rest of the stations are in operation until present.

b. Surface weather charts from January 10 to 13, 2009, provided by the Japan Meteorological Agency (JMA) and archived by the National Institute of Informatics "Digital Typhoon." This data set is available at http://agora.ex.nii.ac.jp.

c. Daily mean sea level pressure (MSLP), zonal (u) and meridional (v) winds, relative humidity (RH), and temperature at multiple levels from the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP-II) from 1979 to 2017, with a $2.5° \times 2.5°$ horizontal grid resolution (https://www.esrl.noaa.gov/psd; Kanamitsu et al. 2002).

d. Six-hourly TC best track data from the Joint Typhoon Warning Center (JTWC; www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php) from 1979 to 2017.
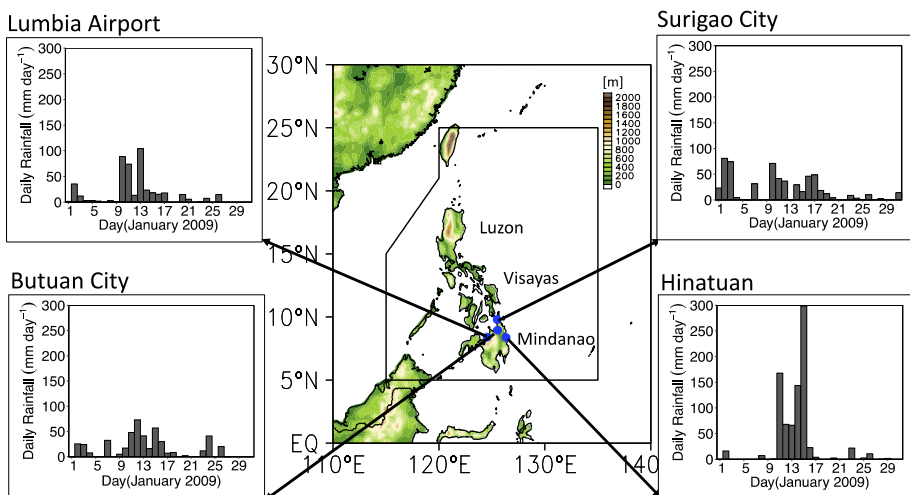

Fig. 1 The topography (m) of the Philippines and the rainfall distribution in the four representative stations over Mindanao Island (Lumbia Airport, Hinatuan, Surigao City, and Butuan City stations) in January 2009. Lumbia Airport is located in Cagayan de Oro City. The solid black boundary surrounding the Philippines is the Philippine Area of Responsibility (PAR)

2.2 Methodology

We examined first the characteristics of the JAN2009 HRF event. Similar to Olaguera et al. (2021; see their Fig. 1), we defined Mindanao Island as the region within 122–127°E and 5–10°N, which encloses the main Island of Mindanao. All anomalies are calculated relative to the 1981–2010 climatology. The significance of the anomalies was assessed by *z*-test. We also examined similar cases to the JAN2009 HRF event that also occurred during January from 1979 to 2017 to test the robustness of the results found in this study and performed lag composite analyses. The significance of the composites was assessed using *t*-test. Further details of the composite analyses are provided in Sect. 3.4.

3 Results and discussion

3.1 Description of the JAN2009 HRF event

On January 2009, Mindanao Island, especially those areas located over the north and northeastern parts, experienced successive HRF events. A tropical depression (TD Auring) crossed over the northeastern part of Mindanao Island from January 3 to 5 and initially filled the rivers in northern Mindanao Island. This was followed by a cold surge shearline that affected Mindanao Island from mid- to late January. Sea swells, numerous landslides, and floods were reported in various parts of the country. It was estimated that about 698,280 people were affected over Mindanao Island and there were 41 reported deaths (Faustino-Eslava et al. 2011). It was reported that the damage cost to agriculture for this month was estimated to be about USD 13.1 million, while that to infrastructure was about USD 22.4 million.

We examined the rainfall time series of the four representative PAGASA stations over Mindanao Island in January 2009 as shown in Fig. 1. Rainfall over the eastern coast (Hinatuan station) started to increase around January 11 almost reaching about 150 mm day^{-1}. The rainfall in this station remained below 100 mm day^{-1} in the succeeding days until January 13 and increased to about 144 mm day^{-1} on January 14. The peak rainfall occurred on January 15 in this station, when the rainfall increased to about 300 mm day^{-1}. The 99th percentile of daily rainfall records for all January from 1979 to 2017 is about 213 mm day^{-1}, indicating that only the rainfall on January 15 exceeded the 99th percentile. Over Surigao station, on the other hand, which is located just to the northwest of Hinatuan station, rainfall increased during the first few days of January to about 80 mm day^{-1}. On January 10, the rainfall reached by about 70 mm day^{-1} and remained around 50 mm day^{-1} until January 17 in this station. The 99th percentile of rainfall of all January from 1979 to 2017 in this station is about 156 mm day^{-1}. However, no days in January 2009 exceeded the 99th percentile value. Over Lumbia Airport, which is located over Cagayan de Oro City, the rainfall starts to exceed 60 mm day^{-1} from January 10 to January 11, followed by a short break on January 12, when the rainfall decreased below 20 mm day^{-1}, and increased again above 100 mm day^{-1} on January 13. Afterward, the rainfall started to decrease below 20 mm day^{-1} on January 15. The 99th percentile of rainfall of all January from 1979 to 2017 in this station is about 57 mm day^{-1}, indicating that the rainfall from January 10, 11, and 13 exceeded this value. Over Butuan City station, the rainfall increased between January 10 and 15, which is consistent with other stations. The 99th percentile of rainfall of all

Fig. 2 Spatial maps of meridional gradient of equivalent potential temperature at 925 hPa ($\nabla\theta_{e925hPa}$; ▶ shades; $\times 10^{-5}$ K m^{-1}) and winds at 925 hPa (vectors; m s^{-1}) for **a** January 10, 2009, **c** January 11, 2009, **e** January 13, 2009, **g** January 15, 2009. b, d, f, and h are for the temperature anomaly (K) at 925 hPa. The scale of the vectors is 20 m s^{-1}. Stippled areas in b, d, f, and h are statistically significant at the 95% confidence level by *z*-test

January from 1979 to 2013 in this station is about 103 mm day^{-1}, and no days in January 2009 exceeded this value. In general, the HRF events were experienced in Lumbia Airport on January 10, 11, and 13 and in Hinatuan station on January 15. In the succeeding sections, we will only focus the discussion in these four days.

3.2 Synoptic conditions during the January 2009 HRF

The lower boundary of the negative meridional gradient of equivalent potential temperature ($\frac{\partial\theta_{e925hPa}}{\partial y}$) can be used to locate the mean position of the cold front (e.g., Olaguera and Matsumoto 2020; Olaguera et al. 2021), as shown in Fig. 2a, c, e, and g and superimposed with the winds at 925 hPa (WINDS$_{925hPa}$). To supplement this, we also looked at the temperature anomaly at 925 hPa as shown in Fig. 2b, d, f, and h. On January 10, 2009 (Fig. 2a and b), north to northeasterly WINDS$_{925hPa}$ are apparent over the South China Sea and northern Philippines. Significant cold temperature anomaly can be seen over the Indochina Peninsula and to the north of the Philippines. The cold front appears to be located around 12°N over the central Philippines. Warm temperature anomaly can be seen to the east of Mindanao Island with significant anomalies located near 140°E. The magnitude of the warm temperature anomaly is larger to the north of 20°N between 140 and 160°E. The wind vectors seem to bifurcate over the northeastern tip of Borneo and accompanied by significant cold temperature anomaly in the same region. A cyclonic circulation can also be seen to the east of mainland Japan along 40°N and over Borneo (i.e., the Borneo vortex). We confirmed from the synoptic weather charts that the cyclonic circulation to the east of mainland Japan is an eastward propagating low-pressure system (Figure S1a), which is followed by a high-pressure system (anticyclonic circulation) to its west. We also examined the MSLP anomalies and found that this high-pressure system is significantly enhanced around the Philippines only on January 13 and 15 (Figure S2). On the western coast of the Philippines, near 10°N, easterly winds converge with the northerlies over the South China Sea. On January 11 (Fig. 2c and d), northeasterly WINDS$_{925hPa}$ are apparent over the Philippines and cold temperatures extend further southward over the northeastern tip of Mindanao Island. The significant cold temperature anomaly, however, is located between 10 and 20°N over Luzon Island in the Philippines, while the significant warm temperature anomaly is located to the south of Mindanao Island. The cyclonic circulation along 40°N also progresses eastward together with the cold temperature anomaly, indicating the cold front nature of this system.

On January 13 (Fig. 2e and f), the cold air mass and cold temperature anomaly extends to 5°N with dominant northeasterly WINDS$_{925hPa}$ flow over the South China Sea and the Philippines. The significant cold temperature anomaly over the Indochina Peninsula extends to the east of Vietnam, while that over the Philippines is only confined to the north of 10°N. The eastern coast of Mindanao Island is under the influence of positive $\frac{\partial\theta_{e925hPa}}{\partial y}$ and temperature anomaly, indicating that warm air mass and warm temperature anomaly are apparent over this region on this day. In contrast, the boundary of the cold front appears to be located over the north and northeastern part of Mindanao
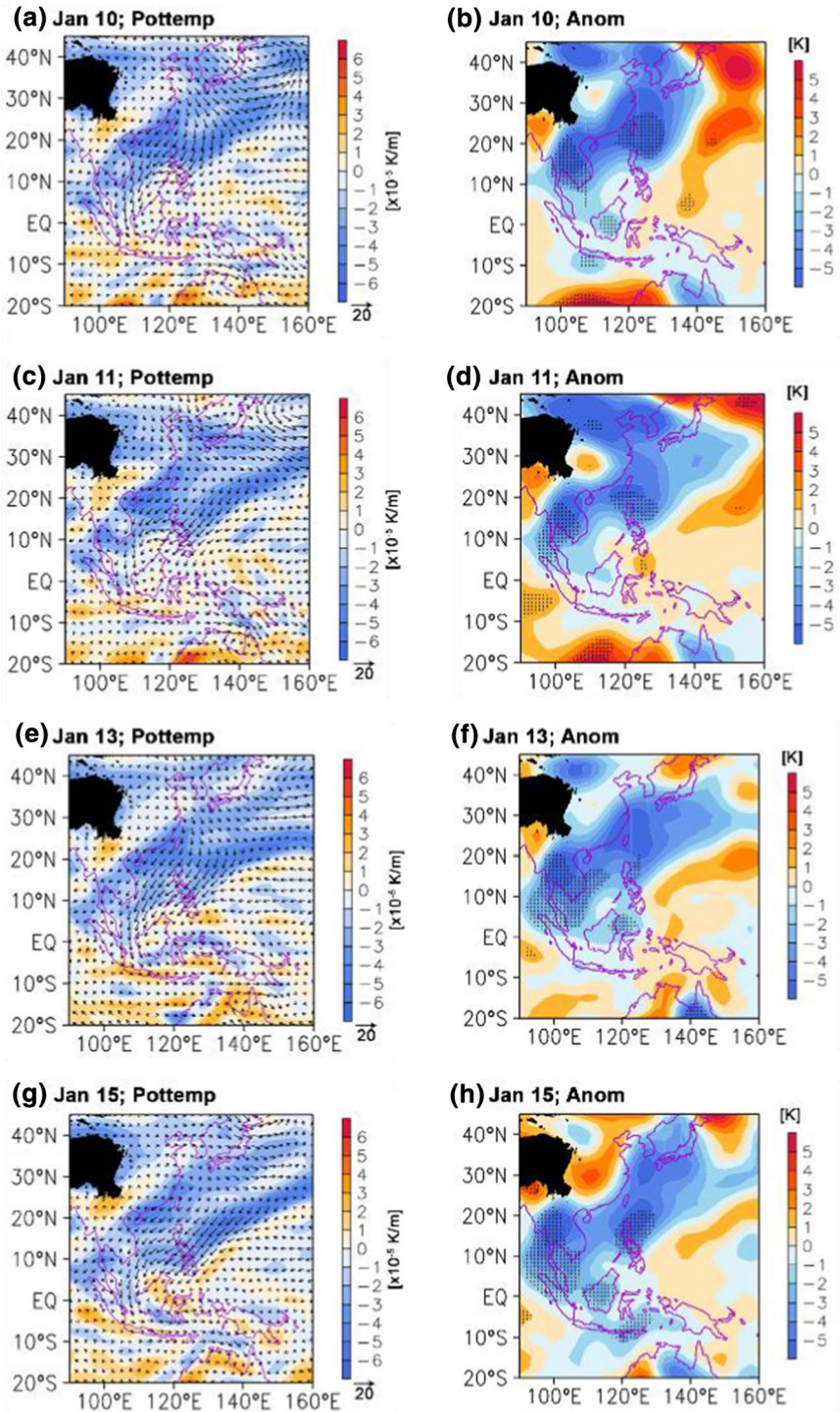
Fig. 3 Spatial maps of winds at 925 hPa (vectors, m s^{-1}) and its magnitude (shades; m s^{-1}) for January 10, ▶ 2009, **a**, January 11, 2009, **c**, January 13, 2009, **e**, January 15, 2009, **g**, and their corresponding climatologies in b, d, f, and h, respectively. The scale of the vectors is 20 m s^{-1}

Island. The January 15 situation (Fig. 2g and h) is almost similar to the January 13 situation, with apparent northeasterly WINDS$_{925hPa}$ over the Philippines, but with more dominant cold temperature anomaly and cold air mass covering the entire Mindanao Island. The significant cold temperature anomaly covers the central and northern Philippines.

Figure 3a, c, e, and g shows the WINDS$_{925hPa}$ (vectors) and its magnitude (shades) from January 10, 11, 13, and 15, respectively, and their corresponding climatologies (1981–2010) are shown in Fig. 3b, d, f, and h. The magnitude of the climatological wind speed is about 5 to 15 m s^{-1} between 5 and 25°N from January 10 to 15, with stronger magnitudes over the south of Vietnam and to the east of the Philippines. Northeasterly WINDS$_{925hPa}$ are also the dominant wind direction. During January 2009, however, the magnitude of the wind speeds reached by about 15 to 30 m s^{-1}, especially over the South China Sea and the Philippines. The strongest wind speed was observed during January 15, 2009 (Fig. 3g and h), when the enhanced northeasterly WINDS$_{925hPa}$ extend from 10 to 20°N. Also note the cyclonic circulation off the coast of northeastern Australia along 15°S. We confirmed that this is a recorded TC (TC Charlotte) during this period.

We also checked the zonal and meridional wind anomalies, and we found enhanced northerly and easterly winds over the country (not shown). The enhanced northerlies might have brought more cold air from the north, while the enhanced easterlies might have brought more warm air from the tropical region. These two interact collaboratively and promote enhanced convergence and ascent as the warm air is pushed upward into the troposphere, leading to enhanced rainfall. To confirm this, we decomposed the temperature advection into its zonal and meridional components according to the following equation:

$$-\mathbf{V} \cdot \nabla T = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} \tag{1}$$

where **V**, T, u, and v are the winds (m s^{-1}), temperature (K), zonal, and meridional components of the winds (m s^{-1}). Since the rainfall peaked on January 13 and 15, 2009, and to save space, we illustrate the temperature advection terms for these days only, as shown in Fig. 4. Positive (negative) temperature advection indicates the air flow from a warmer (cool) region to a cooler (warm) region. A strong positive zonal component of temperature advection ($-u\frac{\partial T}{\partial x}$) can be seen over the eastern Philippines that is oriented in a SW to NE direction and stretches from Mindanao Island at 124°E, 5°N to 150°E, 20°N, confirming that the easterlies advected warmer air to the Philippines (Fig. 4a). Although not as strong as in the eastern coast of the Philippines, a similar positive $-u\frac{\partial T}{\partial x}$ can be seen over the South China Sea. On the other hand, negative meridional component of temperature advection ($-v\frac{\partial T}{\partial y}$) covers a wider area to the north of 10°N, which is consistent with the location of the cold front. Its magnitude is stronger around 135°E, 18°N (Fig. 4b). Negative meridional component of temperature advection is also apparent over the South China Sea and appears to extend to the south of Japan. On January 15, the zonal temperature advection weakens over the South China Sea and strengthens over the eastern coast of the Philippines including the eastern coast of Mindanao Island (Fig. 4c). The meridional temperature advection (Fig. 4d), however, weakens over the South China Sea and the eastern coast of the Philippines, but the latter has a stronger magnitude than the former.
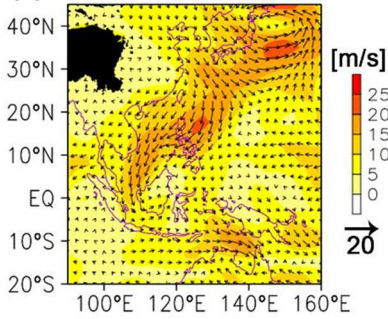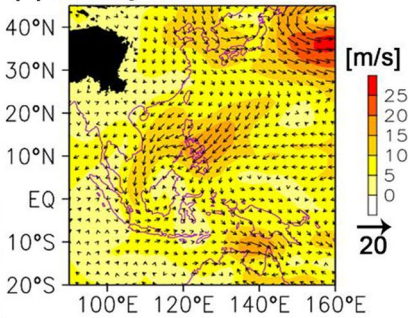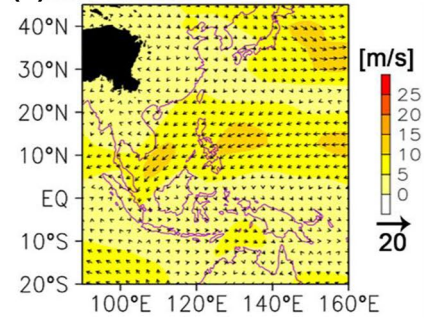
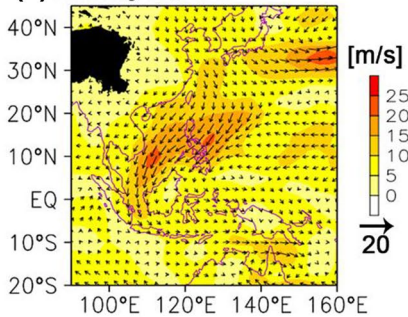(a) January 10, 2009   (b) Jan 10; Clim
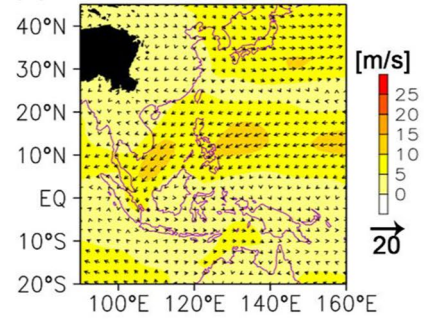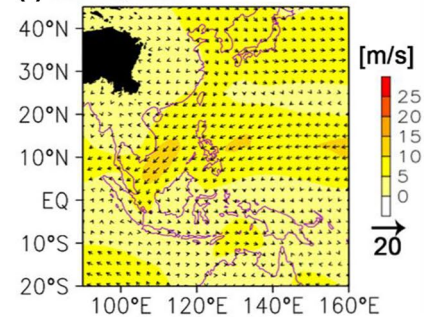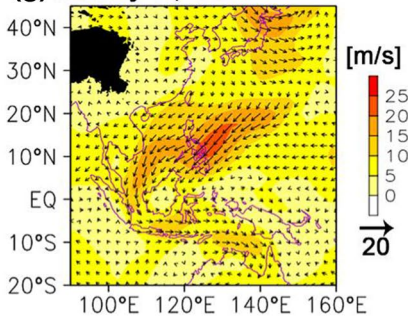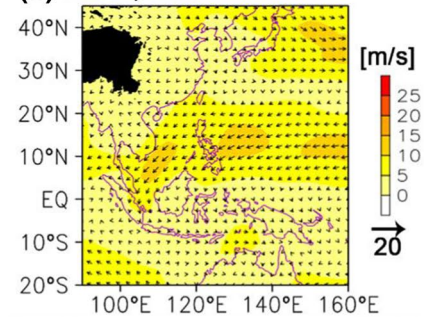
(c) January 11, 2009   (d) Jan 11; Clim

(e) January 13, 2009   (f) Jan 13; Clim
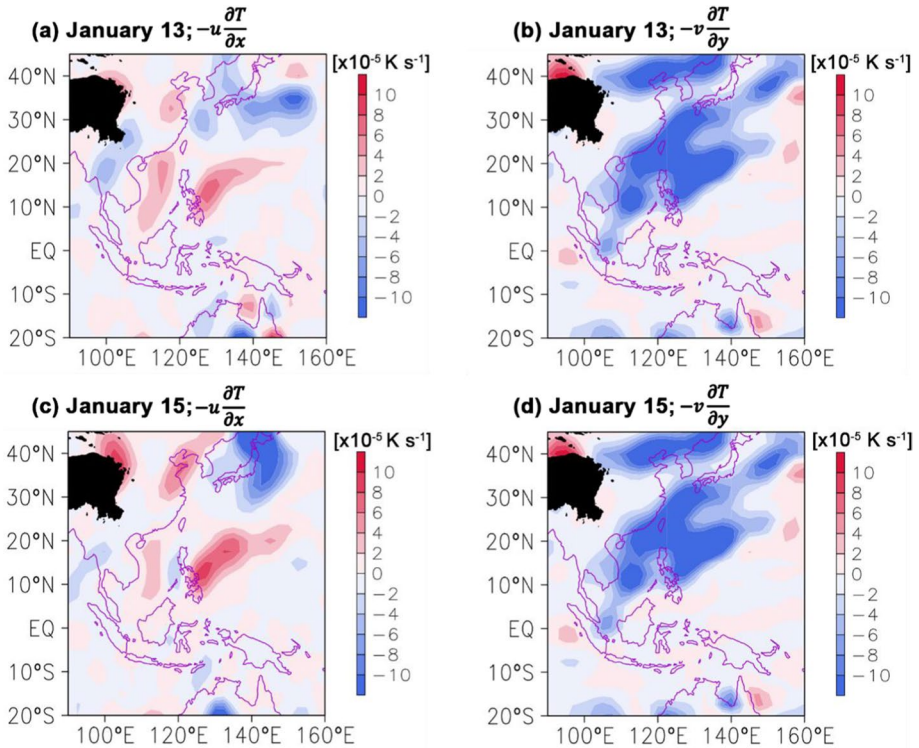
(g) January 15, 2009   (h) Jan 15; Clim

Fig. 4 Spatial maps of zonal $(-u\frac{\partial T}{\partial x})$ and meridional $(-v\frac{\partial T}{\partial y})$ components of temperature advection $(\times 10^{-5} \text{ K s}^{-1})$ for January 13, 2009, **a**, **b** and January 15, 2009, **c**, **d**

Due to density difference, the cooler air sinks and the warmer air is pushed upward because the cool air is denser than warm air. Therefore, the interaction of the cool and warm air will result in enhanced ascent and hence favors enhanced rainfall. To show that the interaction of the warm and cool air resulted in enhanced ascent and rainfall over Mindanao Island, we also illustrate the pressure–latitude cross sections of the vertical velocity, meridional winds, and equivalent potential temperature anomalies averaged between 122 and 127°E for January 10, 11, 13, and 15, in Fig. 5. On January 10 (Fig. 5a), northerlies are apparent at the low levels between 1000 and 900 hPa. Descending flows can be seen between 20 and 30°N, where there is negative equivalent potential temperature anomaly, while ascending flows can be seen between 12 and 15°N. The leading edge of the cold front is located around 15°N. The significant negative equivalent potential temperature anomaly is located between 18 and 25°N below 700 hPa, while the significant positive equivalent potential temperature anomaly is located along 400 hPa between 20 and 25°N. Between 5 and 10°N, where Mindanao Island is located, descending flows can be seen. This may explain why the rainfall is lesser during this day compared to those on January 13 and 15. Also notice the warm air mass in the middle levels, while the lower-level cold air mass is confined to below 500 hPa to the south of 30°N. This pattern appears to be similar to the other days. On January 11 (Fig. 5b), the leading edge of the cold front extends to 10°N. Anomalous descent, however, can still be seen between 5 and 10°N. On January 13 (Fig. 5c), anomalous ascent is apparent between 5 and 10°N. This corroborates
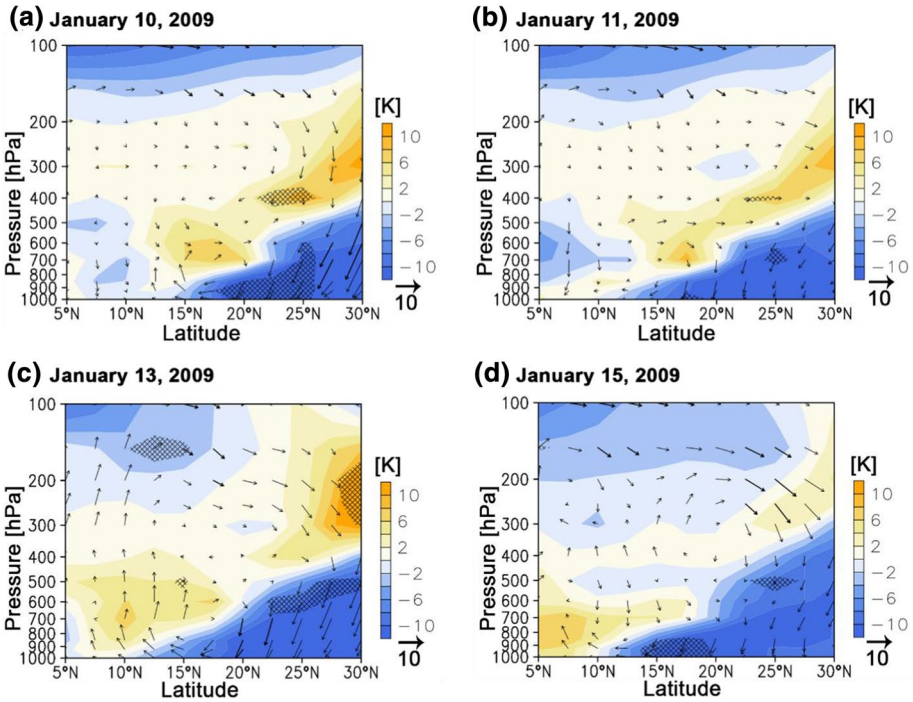
Fig. 5 Vertical profiles of equivalent potential temperature anomaly (shades; K) averaged from 122 to 127°E for **a** January 10, 2009, **b** January 11, 2009, **c** January 13, 2009, **d** January 15, 2009. The vectors are the meridional (m s^{-1}; scale is 10 m s^{-1}) and vertical velocity anomalies (hPa; scale is 10 hPa). The anomalies are relative to the 1981–2010 mean. Stippled areas and bold vectors are statistically significant at the 95% confidence level by z-test

the enhanced rainfall during this day compared to the two aforementioned days. While cold air mass can be seen above 200 hPa on January 10 and 11, this cold air mass extends downward to 300 hPa on January 13. The significant negative and positive equivalent potential temperature anomaly is confined in the middle and upper levels along 600 hPa and 200 hPa, respectively. On January 15 (Fig. 5d), this upper-level cold air mass further expands downward to 350 hPa, while the lower-level cold air mass expands upward to 300 hPa. The ascending air anomalies can be seen to the south of 10°N, while the warm air mass appears to be confined below 500 hPa. The significant negative equivalent potential temperature anomaly is located between 15 and 20°N and below 925 hPa. It is worth mentioning that we also found similar patterns in the vertical cross section of the temperature anomalies, with warmer (i.e., positive) temperature anomaly aloft of the colder temperature anomaly (not shown). This suggests that both the temperature and moisture gradient are important for the anomalous ascent along the cold surge shearline.

3.3 Maintenance of rainfall of the January 2009 HRF event

As shown in Fig. 1, rainfall persisted from January 10 to 17 over Surigao, Lumbia, and Hinatuan stations, although the extreme rainfall only occurred on January 10, 11, 13, and

15 in the latter two stations. What then maintained the rainfall in these days? In this section, we examined the mechanism that maintained the rainfall during the JAN2009 HRF event.

According to Chen et al. (2013) and Olaguera et al. (2021), rainfall is maintained by moisture flux convergence (Q). They further noted that rainfall (P) can be expressed in terms of the horizontal gradient of the velocity potential through the following relationship:

$$P \cong \nabla \cdot Q_D = -\nabla^2 \cdot \chi_Q \qquad (2)$$

where Q_D is the moisture flux divergence (i.e., negative convergence) integrated from 1000 to 300 hPa and χ_Q is the velocity potential. In this section, we examined the χ_Q, Q, and Q_D, following their studies and are shown in Fig. 6.

On January 10 (Fig. 6a), the low-pressure area associated with the cold front, as shown in Figure S1a, that is centered around 140°E, 40°N just off the coast of mainland Japan can be depicted as a region of positive χ_Q and convergent fluxes. To its west is a high-pressure system centered around 110°E, 30°N that can be depicted as a region with negative χ_Q and divergent fluxes. As the low-pressure area moves eastward, this high-pressure system expands eastward and southward. In addition, the zero-contour line of χ_Q lies over southern Luzon Island in the Philippines and extends southward to 10°N to the eastern coast of the country. The convergence region can be seen over Borneo (hereafter, the Borneo
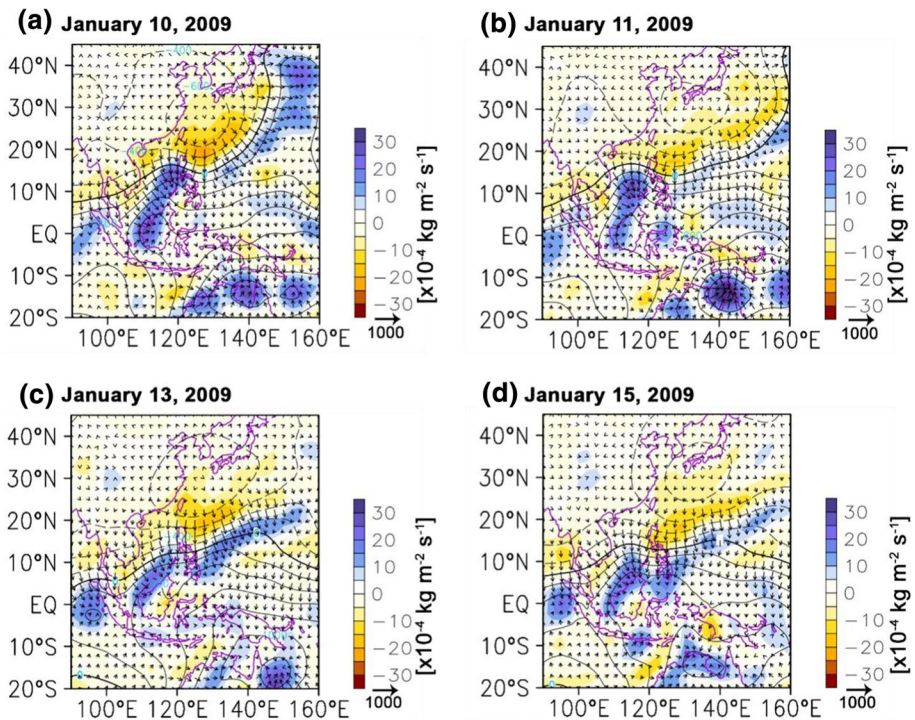

Fig. 6 Spatial maps of vertically integrated moisture flux convergence (Q; shades; ×10⁻⁴ kg m⁻² s⁻¹), velocity potential (χ_Q; contour; ×10⁶ kg s⁻¹), and the divergent component of Q (Q_D; vectors; scale is 1000 kg m⁻¹ s⁻¹) for **a** January 10, 2009, **b** January 11, 2009, **c** January 13 2009, **d** January 15, 2009. The contour interval is of χ_Q is 200×10⁶ kg s⁻¹. The zero χ_Q is indicated by the thicker solid contour line

vortex) and downstream of the northerly flux (Fig. 6a). Over Mindanao Island, Q is small, which is also consistent with the lesser rainfall observed during this day. On January 11 (Fig. 6b), the zero-contour χ_Q further extends to the equatorial region. Enhanced Q can still be seen over the western coast of the Philippines until Borneo. The Q_D on this day extends to 160°E. Similar to the previous day, the Q is also small over Mindanao Island. On January 13 (Fig. 6c), the zero-contour χ_Q is located along 10°N over the Philippines and the convergence region diagonally extends from the equatorial region to 20°N. The Borneo vortex weakens but enhanced northerly fluxes are still apparent over Borneo. Over Mindanao Island, there is enhanced Q, especially on the northeastern coast. On January 15 (Fig. 6d), the enhanced Q covers the whole Mindanao Island, while the zero-contour χ_Q remained along 10°N. In general, the enhanced moisture convergence along the cold surge shearline and downstream of the northerly flux from the anticyclone to the north of the Philippines also played important roles in sustaining the rainfall during this HRF event.

3.4 Climatology of non-TC-related HRF events

In this section, we examined other non-TC-related HRF events that are similar to the JAN2009 HRF event and occurred from 1979 to 2017 to show the robustness of the results found in this study. To do this, we identified the days that satisfied the following conditions. This was applied for all the days of January from 1979 to 2017.

(a) No TC should be located within the PAR (Fig. 1). We only considered those TCs with intensities above the Tropical Storm category (i.e., maximum sustained wind speed exceeding 35 knots) from the JTWC best track archive.
(b) The meridional wind anomaly along 15°N and between 122.5° and 130°E should exceed one standard deviation of the climatological (1981–2010) meridional wind anomaly along the same region. This definition is adopted from Abdillah et al. (2021) who referred to these types of cold surges as the Philippine Sea type.
(c) The daily rainfall in any of the four stations located to the north and eastern Mindanao Island (Lumbia airport, Butuan City, Hinatuan, and Surigao City) should exceed the 99th percentile rainfall of all January from 1979 to 2017.

If the identified days based on the above conditions are consecutive, only the first days of these consecutive events were used for the composite analyses. We also checked the streamline charts of each identified date and removed the days when a cyclonic circulation (or a low-pressure area on the JMA surface weather chart) is located in the vicinity of Mindanao Island. Based on the above criteria, we identified 16 cases including the JAN2009 HRF event. The JAN2017 HRF event found by Olaguera et al. (2021) is not included in these 16 cases. The average duration of the 16 cases is one day. Then, we performed lag composite analyses to elucidate the evolution of these types of HRF event. Lag 0 refers to the mean period of the 16 cases, while the days prior and succeeding to Lag 0 are indicated by a − and + signs, respectively. The significance of the composites was assessed using the *t*-test by comparing the composite mean of the 16 cases and the mean of the other days of January from 1979 to 2017 that were not considered as extreme days.

Figure 7 shows the lag composites of winds at 925 hPa, Q, and MSLP, while Fig. 8 shows the lag composites of $\frac{\partial \theta_{e925hPa}}{\partial y}$. At Lag −3 (Figs. 7a-b, 8a), enhanced northerly winds can be seen over the Southern China, South China Sea, and northern Philippines, which is accompanied by enhanced divergence to the north of 20°N. Based on the
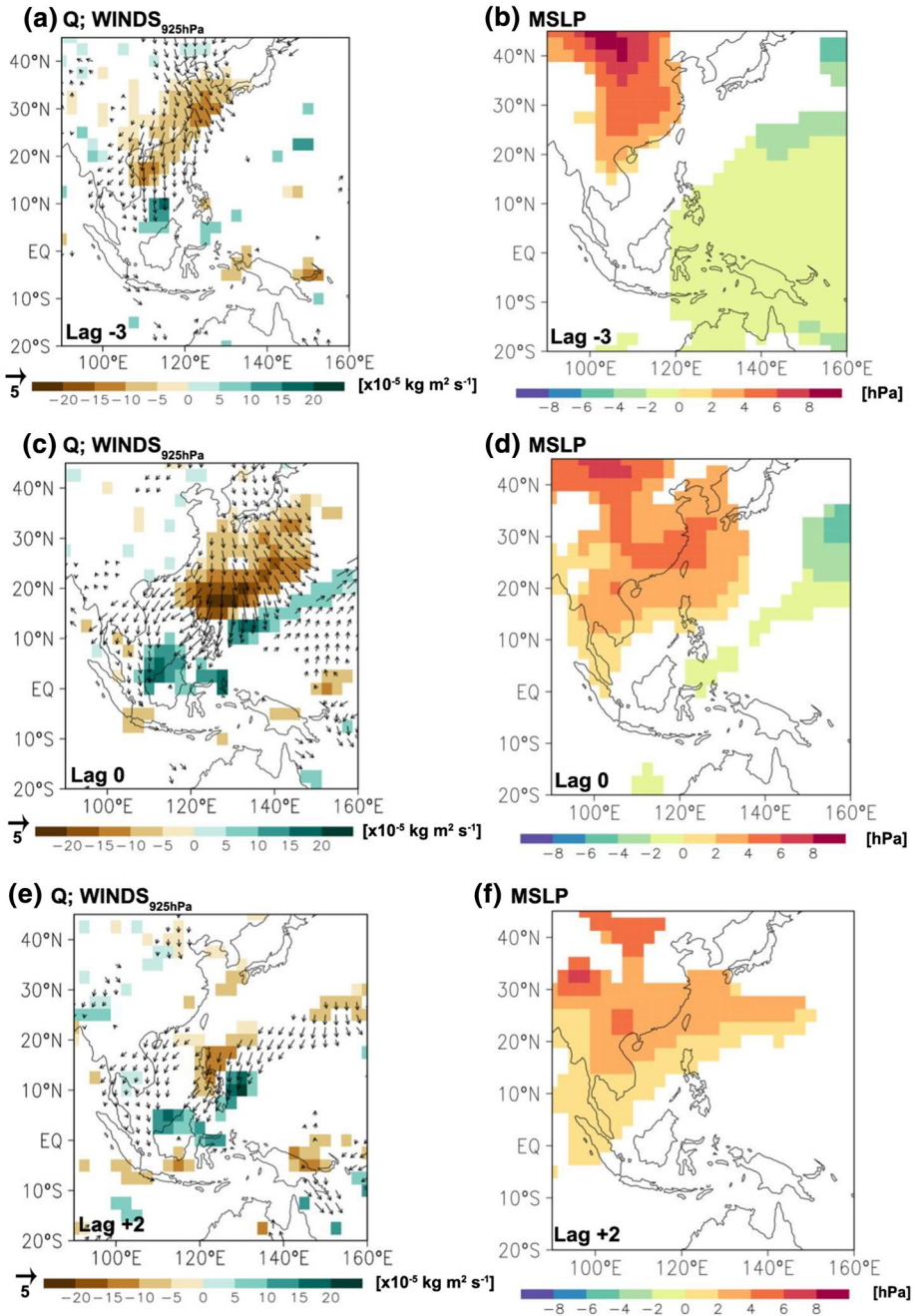
Fig. 7 Lag composites of vertically integrated moisture flux convergence (Q; shades; $\times 10^{-4}$ kg m^{-2} s^{-1}), winds at 925 hPa (WINDS$_{925hPa}$), and mean sea level pressure (MSLP; hPa) for Lag −3 **a**, **b**, Lag 0 **c**, **d**, and Lag +2 **e**, **f**. Only the values that are significant at the 95% confidence level are shown. The scale of the vectors in **a**, **c**, and **e** is 5 m s^{-1}
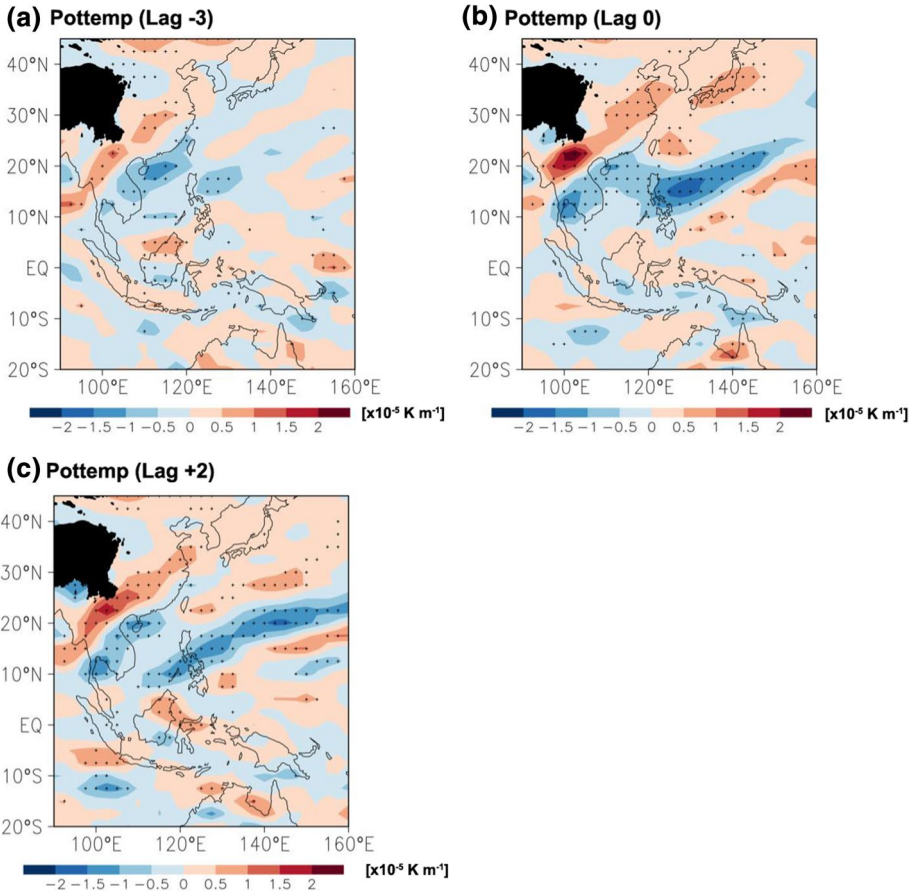
Fig. 8 Lag composites of meridional gradient of equivalent potential temperature ($\times 10^{-5}$ K m^{-1}) for **a** Lag –3, **b** Lag 0, and **c** Lag + 2. Stipples indicate statistical significance at the 95% confidence level

composite plot of MSLP in Fig. 7b, there is a stronger high-pressure system in this region. A low-pressure system, on the other hand, can be seen to the east of 140°E. The boundary of the cold frontal system is located over the central Philippines on the same lag day (Fig. 8a). At Lag 0, the enhanced northerly winds are apparent over the Philippines. An elongated region of enhanced Q can be seen stretching from Borneo to 20°N along the southern periphery of the enhanced northerly winds (Fig. 7c-d). The high-pressure system to the north of the Philippines expanded further south and east and covers the northern Philippines on the same lag day. The boundary of the cold frontal system is located just to the north of Mindanao Island (Fig. 8b). At Lag + 2, the northerly winds weakened relative to those at Lag 0, while Q is still significantly high over Mindanao Island. The high-pressure system expanded further south over the central Philippines (Fig. 7f), while the low-pressure system to the east of 140°E moved further east on the same lag day (Fig. 7f). The boundary of the cold frontal system is located to the north of Mindanao Island, which promotes enhanced Q in this region. We also examined the lag composites of $-u\frac{\partial T}{\partial x}$ and $-v\frac{\partial T}{\partial y}$ and found that they resemble those shown in

Fig. 4, with enhanced $-v\frac{\partial T}{\partial x}$ and $-u\frac{\partial T}{\partial x}$ to the north and northeast of Mindanao Island (Figure S3).

4 Summary and discussion

In this study, we investigated the synoptic conditions during the JAN2009 HRF event over Mindanao Island that were not discussed in the previous works of Faustino-Eslava et al. (2011) and Yumul et al. (2013). This HRF event has been attributed to the effect of a cold surge shearline that is formed at the trailing end of an eastward propagating cold front over the north Pacific. Excessive rainfall was felt on January 10, 11, 13, and 15 over Mindanao Island, where the 99th percentile of rainfall of all January from 1979 to 2017 was exceeded by almost two times, especially at Lumbia Airport in Cagayan de Oro City. Analysis of the rainfall time series in four representative stations over Mindanao Island (Hinatuan, Lumbia Airport, Butuan City, and Surigao City) revealed that the impact of this cold surge shearline is more prominent in mid-January.

Aside from orographic lift and localized convective lifting, the presence of a cold front and low-level convergence are also considered important mechanisms that induce atmospheric ascent and rainfall (https://climate.ncsu.edu/edu/Lift). Deep convection and extreme rainfall often occur when there is enhanced moisture convergence along the leading edge of the cold front and enough moisture in the air. The cool air mass associated with a cold front converges with the warm air mass at the lower level. In addition, the warmer air mass is less dense than the cooler air mass and it is forced to rise above the cooler air mass. As the warm air mass rises, it cools and condenses to produce clouds and rainfall. The enhanced lower level moisture convergence and the buoyancy difference of the air masses collaboratively favored the enhancement of rainfall. This mechanism may be able to explain the JAN2009 HRF event.

Moreover, enhanced easterly and northerly wind anomalies were found over the whole Philippines (not shown). The enhanced easterly winds might have facilitated the transport of warm air from the Pacific Ocean. The northerly winds, on the other hand, were found to be more enhanced on the eastern coast of the country (not shown). These northerly winds might have carried the cooler air that is interacting with the warm air from the easterlies. We confirmed this mechanism by decomposing the temperature advection in terms of its zonal and meridional components. We found strong positive zonal temperature advection that is oriented in a SW–NE direction stretching from Mindanao Island to the eastern coast of the Philippines and a negative meridional component of temperature advection to the north of 10°N, which is indicative of the location of the cold front. The mean position of the cold surge shearline is located along the boundary of negative and positive $\frac{\partial \theta_{e925hPa}}{\partial y}$. This is also the location where there are enhanced moisture convergence and rainfall. Although only the rainfall values on January 10, 11, 13, and 15 were considered extremes, rainfall persisted from January 10 to 17 in the four PAGASA stations. Afterward, rainfall occurred intermittently. Using the integrated moisture flux convergence and velocity potential as proxy for rainfall, we found that the enhanced moisture convergence downstream of the northerly flux from the high-pressure system to the north of the Philippines, might have maintained the rainfall in these days.

We also checked the sea surface temperature anomaly (SSTA) over the Niño 3.4 region (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) and found that the SSTA is below −0.5 °C for five consecutive overlapping seasons from

October of 2008 to April of 2009, indicating La Niña conditions. During La Niña conditions, the warmer SST is located over the western Pacific, while the cooler SST is located in the central and eastern Pacific. The walker circulation is enhanced during La Niña conditions, and rainfall is enhanced over the western North Pacific including the Philippines (Lau and Yang 2003; Lyon et al. 2006). As such, the existing La Niña condition is also favorable for the enhanced rainfall during January 2009 through the enhancement of the Walker circulation.

Mindanao Island appears to experience frequent heavy rainfall events during the northeast monsoon season (e.g., Pullen et al. 2015; Olaguera et al. 2021). Pullen et al. (2015) examined an HRF event in February 2008 over the central Philippines. They found that the collaborative effects of the MJO, Indian Ocean dipole, and the northeasterly cold surge contributed in the 2008 HRF event. A low-pressure area over the Maritime continent (MC-Low) that is associated with an active phase of MJO creates a stronger pressure gradient between the MC-Low and the Siberian Mongolian High, which, in turn, enhances the northeasterly winds. We therefore checked the location of the MJO between January 10 and 13 using the Wheeler and Hendon (2004) MJO index (http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt). In these days, we found that the MJO is located over the western Pacific and has no direct influence on the enhancement of the northeasterly cold surge.

Olaguera et al. (2021) examined the JAN2017 HRF event, which was caused by the interaction of a westward propagating cyclonic circulation over Mindanao Island, eastward propagating cyclonic and anticyclonic circulation between 30 and 40°N, and a stationary anticyclone over the eastern Pacific. These four circulations formed a deformation zone whose confluence region (i.e., the axis of dilatation) was located over northern Mindanao Island. The cold surge shearline was located along this confluence zone and caused urban flooding over Cagayan de Oro City. In addition, during the JAN2017 HRF event, enhanced low-level northeasterly winds were also found over the eastern Philippines similar to those during the JAN2009 HRF event. However, there is no cyclonic circulation present over Mindanao Island during the JAN2009 HRF event, suggesting that even without such cyclonic circulation, extreme rainfall events may still occur over Mindanao Island induced by the cold surge shearline. We examined all extreme cases (i.e., any of the four stations over the northern and eastern Mindanao Island has a rainfall amount above their corresponding 99th percentile values and there is enhanced meridional wind anomaly over the Philippine Sea) during January from 1979 to 2017 and found 16 cases including the JAN2009 HRF event. The lag composites of these 16 cases showed enhanced low-level northeasterly winds to the east of the Philippines, enhanced anticyclone to the north of the Philippines, enhanced Q along the southern periphery of the enhanced northeasterly winds, and enhanced warm and cold temperature advections to the north of Mindanao Island. From these 16 cases, we found ten cases that occurred during La Niña years and no MJO over the Maritime Continent, while there are only two cases that occurred with MJO over the Maritime Continent, but not La Niña years. This implies that the presence of MJO over the Maritime Continent and the La Niña provides favorable conditions for cold surges and extreme HRF events over the Philippines.

Other factors might have also contributed to the JAN2009 HRF event such as the role of urbanization in Cagayan de Oro City. Yumul et al. (2013) mentioned that the JAN2009 HRF event over Mindanao Island has never been experienced by the same region in the past 50 years. Therefore, the impact of land cover change cannot be ruled out (e.g., Promchote et al. 2016; Dado and Narisma 2019). Promchote et al. (2016), for example, found that the monsoon rainfall and tropical cyclone contribution are not

enough to induce the unprecedented 2011 flood in Thailand. They suggested that the anomalous high rainfall during the pre-summer monsoon season, high annual soil moisture, elevated sea level height in the Gulf of Thailand, and water management issues also contributed to this flood event. Using model simulations, Dado and Narisma (2019) showed that the southwest monsoon rainfall can increase rainfall over Metro Manila by as much as 20% due to urbanization. The contribution of land cover change using numerical simulations on the flooding during the JAN2009 HRF event over Mindanao Island will be explored in a future study. In addition, improving the forecast of these types of non-TC-related HRF events using high-resolution numerical models is important for disaster mitigation and will be explored in future works.

Moreover, Chen et al. (2004) showed that the East Asian cold surges exhibit a distinct interannual variability that is closely tied with the SST anomalies over the Niño 3.4 region. In particular, cold surges occur more (less) frequently during warm (cold) ENSO winters. It is also of great interest to explore the interannual variability of the impacts of cold surge shearlines in future studies.

Declarations

Conflict of interests The authors declare no conflict of interest.

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