Cold Surge Pathways in East Asia and Their Tropical Impacts

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ABSTRACT: Cold surge occurrences are one of the robust features of winter monsoon in East Asia and are characterized by equatorward outbreaks of cold air from the high latitudes. Beside greatly affecting weather variability across the Far East, cold surges are of importance for Southeast Asian countries because they can propagate far to the tropics and excite convective activities. However, the tropical responses highly depend on the downstream pathways of the surges. To better understand how cold surges influence tropical weather, we investigate 160 cold surges identified using a quantitative approach during 40 winters from 1979/80 to 2018/19, and then classify them into several groups based on their prominent pathways. At the midlatitudes, we find two groups: one for surges that show clear equatorward propagation of cold air to lower latitudes and the other for surges that turn eastward and bring cold air to the North Pacific. These groups arise due to the strength difference of the Siberian high expansion controlled by cold air blocking near the Tibetan Plateau. The tropical impact is evident in the former group. We perform further classification on this group and find four types of surges based on their pathways in the low latitudes: 1) South China Sea (SCS) surges, 2) Philippines Sea (PHS) surges, 3) both SCS and PHS surges, and 4) blocked surges. They exhibit distinct precipitation signatures over the Maritime Continent, which are driven by interactions between the surges and the pre-existing synoptic conditions over the tropics, particularly the Madden–Julian oscillation (MJO).

KEYWORDS: Synoptic climatology; Cold air surges; Precipitation; Maritime Continent; Intraseasonal variability

1. Introduction

East Asian winter is intermittently intruded by the sudden release of cold airmasses (CAM) from the high latitudes, which affects weather variability across the Far East and the North Pacific. This so-called cold air outbreak or cold surge event typically leads to rapid temperature drops, high pressure, and strong winds for one to several days (Chang et al. 1979; Ding and Krishnamurti 1987; Zhang et al. 1997; Shoji et al. 2014). Severe cold surges are well known for causing huge socioeconomic impacts on the densely populated countries in East Asia (Qian et al. 2018).

Cold surges can penetrate far to the tropical region, inducing convection and precipitation in Southeast Asian countries especially around the South China Sea (SCS) and the Philippines Sea (PHS) (Chang and Lau 1980; Compo et al. 1999; Chang

et al. 2005; Lim et al. 2017), which eventually lead to heavy rainfall and flood events (Wu et al. 2007; Tangang et al. 2008; Yokoi and Matsumoto 2008; Chen et al. 2015a,b). Although there are many studies investigating cold surge impacts, they often used surge indicators defined in the low latitudes—for example, a pressure or northerly wind index in the SCS—instead of in the midlatitudes where cold surges basically come from. The airflow associated with cold surges experiences a long journey from the high latitudes to the tropics; thus the pathways of cold surge are susceptible to downstream synoptic conditions that may control the surge propagation to the tropics (Abdillah and Iwasaki 2019). For impact analysis, most people utilized surges that had already arrived in the low latitudes to ensure connection with the precipitation response. However, forecasters in Southeast Asia would get more advantages by analyzing the midlatitude surge events and their downstream pathways since this would enable them to predict the impacts much earlier, before the surges arrive in the low latitudes.

East Asian cold surges have been studied extensively; their main characteristics and synoptic features are well documented. There are many definitions of cold surge indicators, which use different parameters and vary regionally depending on the purpose of study. However, most of the indicators were defined based on proxies of cold surges. A quantitative method is more preferable because it can directly measure equatorward CAM fluxes (Shoji et al. 2014). By using an appropriate potential temperature threshold, the equatorward CAM fluxes

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are found to strongly correlate with extratropical direct circulation of the mass-weighted isentropic zonal mean (Iwasaki and Mochizuki 2012; Iwasaki et al. 2014), implying their good association with global heat transport. The use of isentropic approach is physically suitable for depicting cold surges because it eliminates warm air mass fluxes. This method also enables us to perform budget analysis of CAM to analyze the genesis/loss mechanisms and the tracks of cold air (Yamaguchi et al. 2019; Liu et al. 2020). Shoji et al. (2014) introduced a quantitative cold air outbreak index to investigate cold surges in East Asia and documented synoptic conditions associated with the surges, but they did not explore the possible impacts of the surges over the tropical regions.

Assessing how well East Asian cold surges affect the tropical regions is our main interest. Most impact studies focused on cold surges that have arrived in the tropics and less attention was paid to the impact of cold surges defined in the extratropics. In our preliminary result (Abdillah and Iwasaki 2019), lagged correlations/regressions between the quantitative cold surge index and tropical convections showed that tropical impacts are statistically significant but the magnitude of anomalies is weaker and the coverage of impact is more confined to the north of equator compared with other studies that used low-latitude cold surge indices. The weak correlation is expected due to nonlinearities between surge magnitude and the tropical responses, which likely appear because of the different downstream pathways of cold surges (Abdillah and Iwasaki 2019). Based on this premise, the current study aims to investigate the variability of impacts of the midlatitude East Asian cold surges by systematically identifying their downstream pathways from their origin. This paper is organized as follows. Section 2 shows data and general method used in this paper. Section 3 discusses two distinct cold surges that exhibit different transports of CAM, which eventually cause active and inactive tropical precipitation responses. Section 4 explores the variability of cold surge pathways in the low latitudes and their impacts. Section 5 summarizes our important findings and some possible future studies.

2. Data and method

a. Data

We utilize the Japanese 55-Year Reanalysis (JRA-55) with 1.25° horizontal resolution as the main atmospheric dataset (Kobayashi et al. 2015). The JRA-55 is available from January 1958. We use a satellite-derived daily precipitation estimation namely PERSIANN-CDR (Ashouri et al. 2015). The PERSIANN-CDR was developed for climate studies that require long-term quasi-global precipitation observation. It is available for the period from 1982 to the present with 0.25° horizontal resolution. To represent large-scale convections, we use daily NOAA interpolated outgoing longwave radiation (OLR) (Liebmann and Smith 1996). It has 2.5° horizontal resolution and is available from June 1974. Daily sea surface temperature (SST) data are obtained from NOAA OISST V2 dataset, which has 0.25° horizontal resolution and covers from 1981 to the present (Reynolds et al. 2007).

The analysis period covers 40 winters from 1979/80 to 2018/19 (December–February). Because SST and precipitation datasets are not available in few early winters, we compensate them with SST and precipitation of the JRA-55. A 6-day low-pass filter (LPF) is applied to all datasets by using Lanczos filter (Duchon 1979). This filtering removes short and possibly weak cold surges, which less likely affect the tropics. The lower limit of 6 days is consistent with Compo et al. (1999), who found that cold surge propagation to the tropics exhibited significant periodicity over a 6–30-day period. However, in this study, we include the intraseasonal variations with periods greater than 30 days as they appear to be important for analysis.

b. Isentropic CAM and cold surge identification

In the isentropic framework, the rate of change in CAM amount DP is controlled by convergence of CAM fluxes $\mathbf{F}$ and diabatic genesis rate G (Iwasaki et al. 2014):

$$\frac{\partial}{\partial t} DP = -\nabla \cdot \mathbf{F} + G, \quad (1)$$

where DP , $\mathbf{F}$, and G are defined respectively as

$$\begin{aligned} DP &\equiv p_s - p(\theta_T), \\ \mathbf{F} &\equiv \int_{p(\theta_T)}^{p_s} \mathbf{v} dp, \\ G &\equiv -\left. \frac{\partial p}{\partial \theta} \cdot \theta \right|_{\theta_T}. \end{aligned} \quad (2)$$

Also, p_s and $p(\theta_T)$ are surface pressure and pressure at threshold potential temperature θ_T , respectively; $\mathbf{v}$ is the horizontal wind vector. The term DP simply indicates the thickness of cold air below θ_T , while $\mathbf{F}$ represents horizontal transport of cold air. Note that G is positive (negative) when diabatic cooling (heating) prevails. By using θ_T of 280 K, Iwasaki et al. (2014) revealed two distinct cold airstreams in the northern winter: the East Asian stream and the North American stream. These streams elongate from north to south, indicating two major pathways of cold surge in the east of the Tibetan Plateau and the Rocky Mountains (Kanno et al. 2015).

Based on the location of the East Asian stream, previous studies developed a cold air outbreak index (CAOI) to identify cold surges in East Asia (Shoji et al. 2014; Abdillah et al. 2017, 2018):

$$\text{CAOI} \equiv \frac{a \cos \phi}{g} \int_{\lambda=90^\circ\text{E}}^{\lambda=135^\circ\text{E}} -F_v d\lambda \Big|_{\phi=45^\circ\text{N}}, \quad (3)$$

where F_v is the meridional component of the CAM flux $\mathbf{F}$ with θ_T of 280 K. The symbols ϕ , λ , a , and g denote latitude, longitude, Earth radius, and gravitational acceleration, respectively. A cold surge is identified when the anomaly of the 6-day LPF CAOI exceeds one standard deviation (σ). The 6-day LPF indicates that only long-lasting cold surges are considered. Using this definition, we find 160 cold surges during the analysis period. A day-lagged composite method is mainly used in this study. Day 0 denotes the day of cold surge occurrence,

FIG. 1. Composite anomalies of CAM amount and its flux from day -2 to $+2$ relative to the peak of cold surge events classified into (a) group 1 and (b) group 2, and (c) their differences. CAM fluxes depicted in (a) and (b) are statistically significant anomalies with a 99% confidence level. Brown contours denote topography with a 1000-m interval.

which is defined as the day when the CAOI reaches a maximum. We then classify the identified cold surges into several groups. The criteria for classification are explained in the following sections. The statistical significance test for the composites is based on two-sided Student's t test.

3. Cold surges evolving into northerly and westerly surges

Case studies conducted in [Abdillah and Iwasaki \(2019\)](#) suggest that a cold surge may or may not take a significant southward pathway. To identify the southward-propagating cold surges, we calculate the magnitude of southward CAM

fluxes at 30°N from 110° to 130°E on day $+1$ after the cold surge occurrences; the longitudinal region based on CAM anomalies in lagged regression analysis. By using this parameter, we classify cold surges into two groups: one that exhibits southward flux anomalies higher than 1σ (104 events) and one that shows anomalies smaller than 1σ (56 events). The former (latter) group simply represents surges that experience strong (weak) southward propagation of cold air to the subtropics.

Figures 1a and 1b show the composite anomalies of CAM and its flux, respectively, for the first group and the second group at day -2 , 0, and $+2$. The center of positive CAM anomalies originates from inland Asia near Lake Baikal, then

FIG. 2. Tracks of cold air domes associated with two groups of cold surges. Black dots denote locations of maxima of standardized CAM anomalies tracked from day -5 (westernmost points) to day $+2$. Triangles denote the location at day 0. Dashed magenta and blue lines connect the maxima of group 1 (G1) and group 2 (G2), respectively. Thick magenta and blue contours denote areas where CAM anomalies of G1 and G2 greater than 1σ at day $+2$, respectively. Gray contours denote topography with a 500-m interval.

moves to the southwest, and finally reaches the northwestern Pacific where a large amount of CAM disappears over the warm Kuroshio. This is a typical synoptic pattern of cold air outbreak events shown in Shoji et al. (2014). At day 0, the peak of CAM anomalies spreads across the midlatitudes in both groups but the coverage of cold air “dome” in the first group extends more southward and westward than that in the second

group. Stronger northerly CAM fluxes in the first group cause such differences in the cold air spread (Fig. 1c), while the second group shows stronger westerly CAM fluxes around the midlatitudes and causes higher CAM amount in the east of Hokkaido Island. These shifting locations of cold air are more visible in the tracking analysis in Fig. 2. The cold air track in the first group is closer to the northern side and eastern side of the Tibetan Plateau, suggesting the possible role of the mountain on the pathway determination. In the sense of CAM distribution, the first group clearly yields greater impact in East Asian land that extends to southern China (Fig. 1c). The following discussions refer the first and the second groups as CAO(NS) and CAO(WS), denoting CAOs that evolve into northerly surges and westerly surges, respectively.

Figure 3 shows the anomalies of mean sea level pressure (MSLP), low-level wind, and temperature. The spatial coverage and temporal evolution of temperature decrease are consistent with the CAM increase in Fig. 1: cold anomalies in CAO(NS) extend to the south and east, whereas cold anomalies in CAO(WS) only extend to the east. In case of wind anomalies, significant northerlies in CAO(NS) prevail and propagate to the tropical regions through the SCS and the PHS. Although the 280-K CAM fluxes mostly diminish in the low latitudes (Fig. 1a), the low-level circulation anomalies persist because of the high pressure extension from the Siberian high that maintains momentum transfer to the equatorial region (Fig. 3a). In CAO(WS), however, the extension of Siberian high is unclear. This weak propagation of high pressure hinders CAM intrusion and northerlies propagation to the low latitudes. We conclude that the southward extension of the Siberian high is the key factor that determines whether a cold air outbreak event evolves into northerly surge or westerly surge.

FIG. 3. Synoptic conditions associated with (a) CAO(NS) and (b) CAO(WS) from day -2 to day $+4$. The variables are composite anomalies of mean sea level pressure (shaded), 925-hPa wind field (vector), and 925-hPa temperature (blue-red contours). Temperature anomaly values are -4° and -2°C (2° and 4°C) for blue (red) contours. Arrows denote significant wind field anomalies at the 99% confidence level. Brown contours denote topography with a 1000-m interval.

FIG. 4. Composite anomalies of the (a) cold airmass amount in north of Tibetan Plateau, (b) high pressure center near Siberia, and (c) low pressure center near Japan. Solid and dashed lines denote composites of CAO(NS) and CAO(WS), respectively. Thick lines are statistically significant anomalies at 99% confidence level. Values in (a)–(c) are the mean values of CAM amount and MSLP anomalies averaged over the three regions shown in (d), respectively.

Takaya and Nakamura (2005) suggested CAM accumulation over the north of the Tibetan Plateau as an important preconditioning for the amplification of the Siberian high during cold surges. This blocking of CAM provides a clue to the physical explanation of the cold surge pathways. To investigate this mechanism, we analyze temporal evolution of

several indices denoting 1) CAM over the north of the Tibetan Plateau, 2) high pressure over Siberia, and 3) low pressure over the northwestern Pacific (Figs. 4a–c). The locations for calculating the indices are shown in Fig. 4d. In CAO(NS) cases, we observe a significant development of CAM index that reaches a maximum at two days before the peak of the high-pressure

FIG. 5. Impacts of two different CAOs in East Asia on day +2. (a),(b) Composite groups of CAO(NS) and CAO(WS), respectively. From left to right: anomalies of CAM flux (vector) and CAM diabatic genesis/loss (shaded), surface heat flux (contour; 100 and 200 W m^{-2} in orange and red, respectively) and SST (shaded); precipitation, and vertically integrated moisture flux from surface to 200 hPa (vector; shadings denote magnitude of meridional component). Vector fields and dotted areas indicate significant anomalous areas at the 99% confidence level.

index at day 0 (Figs. 4a,b). This precursor clarifies the importance of cold air blocking on the Siberian high amplification and cold surge occurrence. The development of cold air and the subsequent high pressure indicates the characteristics of topographically trapped Rossby waves, which then cause strong equatorward surge as the waves break (Compo et al. 1999). It is also worth mentioning that cold surges could have Kelvin wave signature (Nakamura and Doutani 1985). In contrast, CAO(WS) shows a small and insignificant CAM index (Fig. 4a). Less blocking of cold air leads to the weak high pressure development (Fig. 4b) and thus less equatorward outflow. This reduced blocking is probably caused by the northward shift of anticyclone as shown in Fig. 3b. Nevertheless, CAO(WS) shown significant development of low pressure over the northwestern Pacific (Fig. 4c). The low pressure index reaches a peak at day 0, implying that the low pressure center is the main driver of CAO(WS). In a different study related to cold events over China, the surface synoptic patterns of CAO(NS) and CAO(WS) are somewhat similar to East Asian south cold events and north cold events, respectively, as documented in Song and Wu (2017). In an earlier study, Wang et al. (2009) also discussed eastern and southern pathways of cold air but in terms of interannual variability of East Asian trough axis and winter monsoon.

Figure 5 shows several impacts of cold surges over East Asia associated with air–sea interactions and heat exchange. At day +2, the negative anomalies of CAM genesis rate indicate the increase of cold air loss owing to diabatic warming (Fig. 5, first column). Recently, Yamaguchi et al. (2019) showed that the CAM loss during cold surge is attributed to the vertical diffusion heating due to warm surfaces and the condensational

heating due to forced convection. CAO(NS) causes abundant loss of cold air along the Kuroshio that elongates from southern China to the east of Japan, while the loss resulted from CAO(WS) is only limited around Japan region. The differences are also evident in sea surface temperature (SST) and heat flux anomalies (Fig. 5, second column). In CAO(NS), the SST cooling and positive heat flux anomalies are observed from the SCS to the east of Japan. The cooling is not clearly observed prior to day 0 (figure not shown), and thus the above pattern indicates ocean response to cold surges. Takahashi and Idenaga (2013) found time scale dependency of the impact where the ocean response is stronger on the intraseasonal time scale than the synoptic scale. Meanwhile, the SST anomalies are very weak in CAO(WS). Moving to the precipitation field (Fig. 5, third column), CAO(NS) shows significant dry anomalies over the East Asian coast to the northwestern Pacific, except in the western side of Honshu Island along the Japan Sea coast where orographic precipitation often appears. Such pattern also appears in CAO(WS) but in a smaller area. Furthermore, we evaluate the vertically integrated moisture flux anomalies associated with the two pathways (Fig. 5, fourth column). Although the basic nature of East Asian cold surge is cold and dry, the surge gains heat and moisture along its path over the East China Sea and farther downstream. CAO(NS) yields strong equatorward moisture transport, which, interestingly, splits into two paths in the subtropics: one that goes to the SCS and the other one goes to the PHS.

The tropical responses to cold surges are presented in Fig. 6. As expected, the CAO(NS) yields clear intrusion of northerly anomalies and induces significant precipitation anomalies. However, in CAO(WS), the associated circulation and

FIG. 6. Tropical signatures associated with (a) CAO(NS) and (b) CAO(WS) following CAO events (from day 0 to day +4). The variables are anomalies of MSLP (orange contour), vertically integrated moisture flux from surface to 100 hPa (vector), and precipitation (shaded). Dotted areas and arrows denote significant anomalous precipitation and moisture flux, respectively, at the 99% confidence level.

precipitation are insignificant and not clearly organized. The classification successfully separates cold surges that have clear and unclear impacts on the tropics.

Moving forward, our discussion is focused on the impacts of CAO(NS) (Fig. 6a). The northerly moisture flux anomalies expand southward and eastward following the pattern of MSLP anomalies. The circulation anomalies cause the development of three precipitation centers in and around the SCS, which are predominant at day +2 and +4 after the surge occurrence. The first center appears in the east of the Philippines due to islands effect and convergence between the surge and warm easterly trade winds over the Pacific. The second one is located over the SCS and northern Borneo, which is affected by topography and convergence between northerly and easterly surge anomalies. The third center is located farther downstream in the area around Singapore, Peninsular Malaysia, and eastern Sumatra, where the terrain obstructs the surge and causes orographic rainfall.

On the Southern Hemisphere side, precipitation and wind anomalies significantly appear and develop in the southern Maritime Continent, such as the case in the north of Java. It suggests the existence of impact from cross-equatorial flow, though the associated wind anomalies in the Java Sea are not clearly linked to the wind anomalies in the SCS. The cross-equatorial flow is discussed further in the next section. Moreover, we observe that precipitation and wind anomalies in the southern Maritime Continent already appear from day 0 and even earlier (figure not shown). This precursor pattern also

appeared in the composite of all events and regression analyses (Abdillah et al. 2018; Abdillah and Iwasaki 2019). Abdillah et al. (2018) clarified that this signature is associated with the active phase of Madden–Julian oscillation (MJO) that acts as a precursor signal for cold surges.

4. Different pathways in the subtropics

East Asian cold surges often evolve into subtropical surges over the SCS. However, few studies also documented that the cold surges could promote surges over the PHS (e.g., Compo et al. 1999). These different pathways may cause distinct impacts over the tropical regions but research on this topic has gained less attention.

To investigate the possible appearance of surges over the SCS (referred to as SCS-type) and the PHS (PHS-type), we make further classification of the surges in CAO(NS) group. By defining region A over the SCS (15°N, 110°–117.5°E) and region B over the PHS (15°N, 122.5°–130°E) (Fig. 7a, left), an SCS-type surge is identified when the northerly wind anomaly over region A at day +2 or +3 exceeds 0.75σ but the northerly wind anomaly over region B does not exceed 0.75σ ; and the wind direction at region A must be either northerly or northeasterly. A PHS-type surge is identified in a similar manner, except the rules for regions A and B are switched. The rest of the surges are classified into “Both-type” and “Blocked-type” for surges that satisfy the northerly wind enhancement in both regions and neither region, respectively. Therefore, there is a

FIG. 7. Different impact patterns of cold surges over the tropical regions induced by four different subclassifications of CAO(NS): (a)–(d) South China Sea (SCS), Philippines Sea (PHS), Both, and Blocked types, respectively. From left to right panels denote day 0, +2, and +4, respectively. Shadings and the vector field indicate MSLP and 925-hPa wind anomalies, respectively. Dotted areas denote significant MSLP anomalies at the 99% confidence level. Only significant anomalous wind vectors are drawn. Black thick lines in the left panel in (a) denote regions A and B.

TABLE 1. Number of cold surge events and their classifications during 40 winters from 1979/80 to 2018/19.

Cold surge groups and types	Number of events (%)
CAO(NS)	104 (65%)
SCS-type	18 (11%)
PHS-type	19 (12%)
Both-type	44 (28%)
Blocked-type	23 (14%)
CAO(WS)	56 (35%)
Total	160

total of four subclasses of CAO(NS). We identify 18 SCS-type, 19 PHS-type, 44 Both-type, and 23 Blocked-type surges (Table 1). Figures 7 and 8 show the circulation at 925 hPa and MSLP, and the precipitation and moisture flux anomalies associated with those four surge types, respectively.

a. SCS-type

For the SCS-type surges, the propagation of high pressure appears in the tropics but seems more confined to the Indochina Peninsula compared to the composite mean of CAO(NS) (Fig. 7a). In the east of the Philippines, overexpansion of the high to the southeast suppresses the development of northerly surge over the PHS. The northerlies anomalies are dominant over the western side of the SCS, which results in precipitation anomalies over Peninsular Malaysia, east of Vietnam, and the northern Philippines (Fig. 8a).

The SCS-type mostly appears in early winter and greatly reduces in late winter (Fig. S1 in the online supplemental material). In early winter, the background cold tongue—a region of low SST in the SCS elongated from north to south due to evaporative cooling induced by prevailing winter monsoon—is not fully developed yet (Chen et al. 2003; Koseki et al. 2013) and it could be one of the reasons why the southward propagation looks somewhat suppressed in the SCS. At day +4 along the 10°N, although not statistically significant, there is a trough in the north of Borneo and the Philippines (Fig. 7a). Based on the examination of each SCS-type surge, this trough likely indicates low pressure vortices (an example is shown in Fig. S2). By looking at the synoptic map of each surge, we identify 11 out of 18 SCS-type surges exhibiting the vortices, but their locations are rather inconsistent, thus causing the obscure pattern of troughs in the composite map. The vortex consequently deflects the surge to the western side of the SCS and triggers the development of easterlies in the PHS. Chen et al. (2015a,b) documented detailed studies on the interactions between cold surges and vortices, which may lead to heavy rainfall/flood events over Southeast Asia.

b. PHS-type

For the PHS-type surges, the significant intrusion of high pressure over the SCS is very limited to the north of 15°N (Fig. 7b). The high anomalies clearly propagate toward the PHS but not as far as those of the SCS-type. This surge type results in the amplification and eastward extension of precipitation over the east of Philippines, whereas there is no sign of positive precipitation anomalies in and around the SCS (Fig. 8b).

Interestingly, there are large-scale dry anomalies persisting from day 0 in the western Maritime Continent (Fig. 8b). The dry anomalies indicate anomalous subsidence, causing low-level high pressure and divergence, which in turn hinders surge propagation over the SCS. Due to its large-scale feature, the dry anomalies suggest a possible role of the MJO. Figure 9b shows evolution of intraseasonal tropical OLR anomalies (30–80-day bandpass filtered). At and around day 0, we observe a clear and significant dipole pattern of MJO, indicating that the active phase of western Pacific MJO coincided with the PHS-type surges. Moreover, we observe a smaller-scale low pressure center in the east of PHS at day 0, which appears to support the development of PHS-type (Fig. 7b). Similar to the SCS-type, the low pressure center indicates composite of vortices but they exist in the PHS instead of the SCS (Fig. S3).

c. Both-type

This type accounts for the majority of CAO(NS) group. Figure 7c shows that the northerly wind anomalies exhibit strong southward propagation in both the SCS and the PHS. The intrusion of high pressure appears to be similar with the composite mean of all CAO(NS) but it moves farther southward, crossing the equator at day +2 to +4. The high pressure is accompanied by large-scale low pressure anomalies that elongate from the southeastern Indian Ocean to the northwestern Pacific. These low pressure anomalies provide extra north–south and west–east pressure gradient forces that amplify northerlies propagation toward the SCS and the PHS. Furthermore, the SCS northerlies clearly propagate to the Java Sea and converge with the westerly anomalies in the southern Maritime Continent. The precipitation anomalies caused by this type are much greater and wider than the other types (Fig. 8c). The cross-equatorial surge causes further transport of moisture and thus increases precipitation over the southern Maritime Continent, especially over Java Island, the Lesser Sunda Islands, and the surrounding seas. The cross-equatorial surge is a well-known phenomenon in Southeast Asia and first well documented in Hattori et al. (2011) by using a surge index near the equator. Here, we clarify its connection with the extratropical cold surges.

The tropical large-scale low pressure anomalies indicate the signature of active phase of the Madden–Julian oscillation. Figure 9c shows the co-occurrences of the Both-type surges and significant MJO-related OLR anomalies over the Maritime Continent. In addition, the appearance of westerly anomalies in the ITCZ supports the evidence of the MJO (Fig. 7c) (Wheeler and Hendon 2004). The MJO induces an unstable environment that provides favorable condition for convective activity. Previous studies showed that the degree of impacts of SCS surges increases largely when the MJO is active over the Maritime Continent (Hattori et al. 2011; Lim et al. 2017).

d. Blocked-type

CAO(NS)s that do not evolve into either SCS-type or PHS-type are categorized as Blocked-type surges. The composite map shows that the associated southward propagation of high pressure anomalies is weak and limited around 20°N (Fig. 7d). Therefore, the precipitation

FIG. 8. As in Fig. 7, but for precipitation (shadings) and moisture flux (vector) anomalies.

patterns show no significant enhancement in the Maritime Continent (Fig. 8d).

We observe southwesterly anomalies extending from the Bay of Bengal to the East China Sea, which appear to counteract

the northerly surges. The southwesterlies are generated by low pressure anomalies centered around southern China and the Indochina Peninsula at day 0. In some cases, the low pressure anomalies are coupled with an anomalous anticyclone over the

FIG. 9. Large-scale evolution of tropical OLR anomalies averaged over 15°S–15°N from day –20 to day +20. Contours show the 6-day low-pass filtered OLR, while shadings denote intraseasonal MJO OLR (30–80-day bandpass filtered). Dotted areas indicate significant intraseasonal OLR anomalies at 99% confidence level.

PHS, thus enhancing the southwesterlies (Fig. S4). On an interannual time scale, the existence of a PHS anticyclone has been linked to the weakening of the East Asian winter monsoon (Wang et al. 2000). Furthermore, we find that few surges coincide with dry phase of MJO over the Maritime Continent (figure not shown). This is consistent with Lim et al. (2017), who found a reduction in cold surge frequency over the SCS during the suppressed phase of MJO over the Maritime Continent. Large-scale divergence induced by the MJO hinders the development of incoming northerlies.

5. Concluding remarks

This study investigates the impacts of midlatitude East Asian cold surges over the tropical regions by systematically identifying and classifying their downstream pathways. By collecting long-lasting cold surges (6-day LPF), we divide the surges into two groups from the perspective of CAM equatorward intrusion: CAO(NS) and CAO(WS). CAO(NS) is cold air outbreaks that evolve into northerly surges, which transport large amount of cold air to the lower latitudes and

cause great impact over the southern part of East Asia. Its associated northerly wind triggers significant positive precipitation anomalies over the tropical region. Meanwhile CAO(WS) is cold air outbreaks that evolve into westerly surges, which yield an impact that is limited to northeastern China, Japan, and the North Pacific Ocean. The distinct pathways are caused by the existence of southward extension of the Siberian high, which is affected by the blocking of CAM over the north of the Tibetan Plateau.

Further classification is applied to the CAO(NS) group to explore the variability of impacts over the tropical regions. By defining two surge indices over the SCS and the PHS, we introduce four types of CAO(NS): SCS-type, PHS-type, Both-type, and Blocked-type. The differences arise due to interactions between the surges and the pre-existing synoptic conditions over the tropical regions. The resulting tropical responses vary between the surge types. A notable feature is shown by the Both-type surges that yield cross-equatorial flow and thus increase precipitation in the south of equator. The Both-type surges occur due to the supporting effect of large-scale low pressure associated with the active MJO phase over the

FIG. 10. An illustration depicting surge pathways associated with cold surges or cold air outbreaks (CAO) in East and Southeast Asia. NS and WS denote northerly and westerly surges. SCS-type and PHS-type denote surges over the SCS and the PHS; Both-type and Blocked-type denote surges that appear in both regions and neither region. The percentage is based on total cold surge cases during 40 winters from 1978/79 to 2018/19 (see Table 1).

Maritime Continent. Figure 10 summarizes all the surge pathways. The surge types and their associated synoptic patterns identified in this study can assist forecasters in predicting cold surge impacts over Southeast Asia.

This study improves our understanding on the remote interactions between cold surges and the MJO. In Abdillan et al. (2018), we found that the frequency of cold surges is dependent on certain phases of MJO, where the inland cold surges occur mostly when the MJO is crossing the Maritime Continent. Here we find that the Maritime Continent MJO can alter the impact of cold surges. As the surges modify tropical convection, it is possible that this surge-induced anomalous convection changes the MJO activity, which can be regarded as a feedback of East Asian cold surges to the MJO. Few studies have shown evidence that subtropical surges can strengthen the MJO over the Maritime Continent and the western Pacific (Chen et al. 2017; Pang et al. 2018). The possible two-way interactions between the MJO and extratropical cold surges would be interesting for future study.

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