The Extreme Cold Anomaly over Southeast Asia in February 2008: Roles of ISO and ENSO*

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ABSTRACT

A record-breaking, long-persisting extreme cold anomaly (ECA) over Southeast Asia, accompanied by an intraseasonal convection over the Maritime Continent, is identified during the La Niña mature phase in February 2008. The cause of the ECA, in particular the role of the intraseasonal oscillation (ISO) and El Niño–Southern Oscillation (ENSO) on the ECA, is investigated by diagnosing observations and conducting numerical experiments.

The ECA is associated with an enhanced prolonged Siberian high (SH) and a persistent northerly anomaly over Southeast Asia. In contrast to conventional cold surges, which are characterized by a synoptic time scale (less than 10 days), the northerly anomaly associated with the ECA persisted for a month or so. The onset of the northerly anomaly is concurrent with a phase change of an ISO over Sumatra. Unlike the normal ISO that continues its eastward journey, the convection associated with this ISO stationed there during all of February 2008. Numerical experiments with an anomaly atmospheric GCM suggest that the ISO heating over the Maritime Continent is responsible for initiating and maintaining the northerly anomaly.

The westward progression of the La Niña is crucial for blocking the ISO. The circulation and SST anomalies associated with the La Niña moved westward at a speed of about 15° longitude per month. By early February, the suppressed convective anomaly had moved to the far western Pacific. The westward shift of the cold episode prevented the ISO from moving farther eastward. In addition to its blocking effect, the La Niña also enhanced the heating over the Maritime Continent through the anomalous Walker circulation. Therefore, it is the combined effect of the ISO and ENSO that maintained a prolonged positive heating anomaly, which resulted in a persistent northerly anomaly and thus the ECA.

1. Introduction

The East Asian winter monsoon (EAWM) is one of the most remarkable circulation systems over the winter hemisphere, which significantly affects the temperature and precipitation over eastern China, Taiwan, Korea, Japan, and the surrounding region. During the EAWM, strong northerly winds and anomalously low temperature dominate the synoptic weather from Siberia to south China (Chang et al. 1979; Boyle and Chen 1987; Ding 1994; Zhang et al. 1997). Among the synoptic disturbances, the cold surge, characterized by a succession of cold air outbursts from the Siberian high (SH), is the most dramatic weather event, which always leads to a sharp temperature drop and disaster (Chan and Li 2004; Chang et al. 2006).

The EAWM undergoes a wide range of temporal scales with periods from synoptic time scales to intra-seasonal oscillation (ISO; Murikami 1979; Zhang et al. 1997; Compo et al. 1999; Chan and Li 2004). However, the cold surge frequently occurs with a transient time scale, and the temperature drop caused by a cold surge rarely persists for more than two weeks (Zhang et al.
1997; Compo et al. 1999; Chan and Li 2004). In February 2008, an extreme persistent cold anomaly (ECA) accompanied by a long-lasting northerly anomaly and a sequence of cold advection occurred over Southeast Asia. The ECA persisted for nearly one month, which not only broke the lowest temperature record for the past 50 yr but also resulted in numerous agriculture and fishery losses over the Southeast Asia. Particularly, nearly 90% of fishes around the coastline of Penghu (23.3°N, 119.3°E), a small island west of Taiwan, died in this cold event. During the occurrence of the cold event, prominent large-scale atmospheric and oceanic anomalies are identified. It is noted that the initiation of the ECA was concurrent with the arrival of an eastward-propagating ISO, which originated from the equatorial western Indian Ocean, at Sumatra. The coincidence between the ISO and the cold air outbreak implies that they might be related (Hsu et al. 1990; Chang et al. 2005).

Far from the Indian Ocean, a strong cold SST anomaly (SSTA) appeared over the equatorial eastern Pacific and peaked in February 2008 during the ECA. It is well known that a La Niña tends to enhance convection over the Maritime Continent through a so-called atmosphere bridge or anomalous Walker circulation (Klein et al. 1999; Alexander et al. 2002). The interannual variation of EAWM is significantly correlated with the Southern Oscillation index (SOI); that is, a low (high) SOI event coincides with a weakened (strengthened) EAWM (Zhang et al. 1997). A cyclonic circulation anomaly over the Philippine Sea associated with a La Niña tends to reinforce the northerly over the South China Sea and thus enhances the winter monsoon (Wang et al. 2000; Lau and Nath 2003, 2006).

The variation of EAWM is also well linked to the ISO through the tropical–midlatitude interaction (Pan and Zhou 1985; Hsu et al. 1990; Compo et al. 1999; Kiladis and Weickmann 1992; Meckel et al. 1996; Jeong et al. 2005; Pan and Li 2007). For example, the temporal variation of surface temperature anomalies at Guangzhou in southern China shows a clear 30–60-day oscillation (Li 1989). By using geostationary meteorological satellite brightness temperature and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis wind, Chang et al. (2005) demonstrated that the low-level northerly anomaly over the South China Sea is well correlated with the ISO phase, exhibiting more frequent cold surge events during the ISO wet phase. The finding above indicates that the ISO-related tropical heating may significantly affect the low-frequency variability of the EAWM.

While many previous studies examined the separate impacts of the ENSO and ISO on the EAWM, how the ENSO modifies the ISO to affect the EAWM is less discussed. Tam and Lau (2005) analyzed the modulation of the Madden–Julian oscillation (MJO) by ENSO from both observations and model simulations and found that the MJO becomes slower and penetrates farther eastward into the central Pacific during warm episodes, which is consistent with the previous finding reported by Anyamba and Weare (1995). Based on a modeling study, Lau and Nath (2006) demonstrated that the leading ISO mode of the EAWM flow is suppressed (enhanced) in El Niño (La Niña) winters. The coexistence of the ECA, La Niña, and ISO in February 2008 suggests that both the ISO-related tropical heating and the Pacific cold SST are important in causing the ECA. The rest of this paper is organized as follows. In section 2, we describe the data and model used in this study. The large-scale anomalies associated with the ECA are documented in section 3. In sections 4 and 5 we investigate the relationship between the ISO and the ECA based on an observational analysis and numerical experiments respectively. The influence of ENSO on the ISO and ECA is addressed in section 6. Finally, a concluding remark and discussion are given in the last section.

2. Data and model

Daily NCEP–NCAR reanalysis wind, temperature, and geopotential height (Kalnay et al. 1996) and National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature (Smith et al. 1996) are used as major data in this study. The outgoing longwave radiation (OLR) 2.5° × 2.5° daily data (Liebmann and Smith 1996, retrieved from ftp://ftp.cdc.noaa.gov) are adopted for analyzing the ISO. Here the ISO field is derived from the 20–70-day filtered data. Beside the grid data, station data in Hong Kong (22.15°N, 114.15°E), Guangzhou (23.1°N, 113.2°E), and Taipei (25°N, 121.5°E) are used to verify the ECA event.

To demonstrate the role of ISO on the initiation and the maintenance of ECA, a series of numerical experiments is carried out by prescribing an idealized diabatic heating field in an anomaly atmospheric general circulation model (AGCM). The anomaly AGCM was constructed based on the dynamical core of the Geophysical Fluid Dynamics Laboratory, which has been used in previous studies (e.g., Wang et al. 2003; Jiang and Li 2005; Li 2006). The model is a global spectral model with a T42 horizontal resolution (128 × 64).
The anomaly AGCM is similar to a linearized model, in which a three-dimensional (3D) climatological winter [December–February (DJF)] mean basic state is prescribed and does not change during the integration. Vertically there are five equally distributed sigma levels. A strong momentum damping with a decaying time scale of 1 day is applied in the lowest model level to mimic the planetary boundary layer dissipation, and in the free atmosphere a Rayleigh–Newtonian damping of an e-folding time scale of 10 days is applied in the momentum–thermodynamic equations.

3. Large-scale anomalies associated with ECA

In this section, we first identify the ECA from the grid and station data and then document the major characteristics of the large-scale circulation anomalies associated with the ECA. The distribution of the 1000-hPa temperature anomaly in February 2008 (Fig. 1a) shows a south–north-oriented dipole like pattern over the Eurasia, with a broad negative anomaly extending from west Tibet to the East Asian coast and a positive anomaly in high latitudes (north of 50°N). Note that the strongest cold anomaly appeared southeast of the Tibetan Plateau over Southeast Asia. The time series of the area-averaged (box in Fig. 1a) monthly temperature reveals that this cold event is the coldest February during 1949–2008 (Fig. 1b). Figure 1c further shows that the number of very cold days (≥−1σ) exceeds 22 in February 2008, the highest among the last 50 yr.

The daily minimum temperature of Hong Kong station (Fig. 2) shows that the long-persisting cold anomaly was initiated on January 24 and reached the maximum deviation (−7°C) on February 12, which is approximately 3σ (σ = 2.6°C) lower than the climatology. Figure 2 also illustrates that the surface temperature is lower than the climatology for all of February. A similar feature appeared in Guangzhou and Taipei stations. Thus, both the station and grid data confirm that the cold event in February 2008 is the most extreme longest-persisting cold event.

The spatial distribution of the sea level pressure (SLP) anomaly exhibits a similar pattern to the temperature anomaly but with an opposite sign (Fig. 3), indicating that the cold anomaly was associated with a high surface pressure anomaly or vertically integrated cold air mass. In the midtroposphere, a robust positive height anomaly appeared over Lake Baikal, signifying an intensified SH (Takaya and Nakamura 2005). To the east of the positive anomaly, a negative height anomaly occurred over Japan, implying the enhancement of the East Asian trough during the ECA. Such large-scale conditions (i.e., the enhanced SH and East Asian trough) are well known as the favorable conditions for the cold surge southward penetration (Compo et al. 1999; Chan and Li 2004). The height anomaly has a warm core and a barotropic vertical structure (not shown), suggesting that the warm anomaly north of SH (Fig. 1a) was attributed to the persistent height anomaly over Lake Baikal.

In the lower troposphere, significant northerly anomalies appeared over Southeast Asia (Fig. 3). The time series of the temperature and northerly anomalies averaged over Southeast Asia (10°–25°N, 160°–120°E) reveals that the prolonged temperature anomaly in February 2008 is coherent (in phase) with the northerly anomaly (Figs. 4b,c), while the enhanced SH preceded the temperature and wind anomalies (Figs. 4a,b). A correlation analysis shows that the temperature anomaly is significantly correlated with the northerly anomaly (cr = 0.72, Table 1). The weak relationship between the SH and the northerly anomaly (cr = −0.19) suggests that the persistent northerly anomaly is not triggered by the pressure surge, which usually occurs in higher-frequency cold air breaks (Zhang et al. 1997; Compo et al. 1999).

It is interesting to note that the temperature anomaly and the northerly anomaly turn sharply from a fast (<2 weeks) fluctuation to a slower fluctuation during the initiation of the ECA (shading in Figs. 4b,c). A wavelet analysis confirms the switch of the oscillation frequency and shows the slower fluctuation is at a period of nearly 30 days (not shown). These results imply that the northerly anomaly and the ECA are possibly linked to the tropical ISO forcing. In the following sections, we will demonstrate that the ISO-induced heating is indeed responsible for the initiation and maintenance of the ECA.

4. Initiation and maintenance of ECA: Role of ISO

The Hovmöller diagram of the OLR anomaly averaged over 15°S–5°N shows two eastward-propagation convective-phase ISO signals (see arrows in Fig. 5a). The first one was initiated in early December 2007 and then propagated eastward from the western Indian Ocean to the central Pacific. The second ISO was also originated from the western Indian Ocean, but after it moved to the Maritime Continent it stayed there during all of February 2008 and did not continue moving eastward.

The Hovmöller diagram of the 1000-hPa temperature anomaly averaged over 110°–120°E (Fig. 5b) clearly indicates a connection the ISO phase and the temperature anomaly south of 20°N; that is, during the wet phase of the ISO the convective heating over Sumatra induced
FIG. 1. (a) Distributions of 1000-hPa temperature anomaly over Eurasia in February 2008. The areas marked by “+” indicate the temperature anomaly greater than a 95% confidence level. (b) Interannual variation of the averaged (box in (a)) 1000-hPa temperature anomaly in February from 1949 to 2008. The horizontal lines denote the threshold of the 95% and 99% confidence level, respectively. (c) Accumulated days of the daily 1000-hPa temperature lower than $-1\sigma$ from the February climatology. Only the years of the February mean temperature lower than $-1\sigma$ are listed. The confidence level is determined based on a $t$ test, the extreme cold events listed in (c) are chosen as a sample, and the 95% confidence level is 2.3.
anomalous northerlies over Southeast Asia (Fig. 4c), which advected the cold air southward, leading to the ECA. Note in Fig. 5b that a significant cold anomaly appeared around 30°N in mid–late January, which was attributed to record-breaking snow and freezing rain storms leading to a numerous devastating disasters over central and south China. However, this cold anomaly was blocked in the extratropics (north of 20°N) and did not

![Daily Minimum Temperature of Hong Kong](image)

Fig. 2. The time series of the daily averaged minimum temperature during 1 Jan 2008 to 28 Feb 2008 for the Hong Kong (22.15°N, 114.15°E) station. The gray line represents the climatological daily minimum temperature.

![500hPa-H & slp Anomaly](image)

Fig. 3. Same as in Fig. 1, but for the 500-hPa height (contour), 1000-hPa wind (vector), and the SLP (shading) anomalies. The areas marked by “+” indicate the sea level pressure anomaly greater than a 95% confidence level. Only the anomalous wind speed greater than 1 m s⁻¹ is plotted. The contour interval is 20 m.
FIG. 4. The time series of (a) the SH index, (b) the averaged 1000-hPa temperature, and (c) the averaged 1000-hPa meridional wind. The light (dark) shading indicates values above (below) the climatology. The SH index is defined as the averaged SLP over 40°–60°N, 80°–120°E; the temperature and northerly are averaged over 10°–25°N, 100°–120°E. The gray shading in (a) denotes the periods of the enhanced SH and represents the ECA in (b) and (c). Here, for simplicity, the same domain is used for the temperature and wind anomalies. From Figs. 1a and 3 it is noted that the maximum northerly anomaly is located slightly south of the maximum temperature anomaly.
penetrate southward into Southeast Asia until the ISO over the Maritime Continent turned from a dry to a wet phase (Fig. 5).

To further demonstrate the relationship between the tropical heating and the ECA, we separate the ISO into two phases, a dry phase and a wet phase, based on the convection activity over the Sumatra longitudes (90°–120°E, see Fig. 5a). The spatial patterns of the OLR and low-level wind anomalies show approximately a mirror image between the wet and dry phase (Figs. 6a,b). In the dry phase, the convection over Sumatra was suppressed. Near the equator, easterly anomalies occurred from the coast of Sumatra to Madagascar while southerly anomalies appeared over Borneo, the Philippines, and the South China Sea. In the wet phase, the convection over Sumatra was enhanced and the wind anomalies over the equatorial Indian Ocean reversed abruptly from easterlies to westerlies that converged onto the anomalous convection center. Pronounced northerly anomalies appeared from central China all the way to the southern South China Sea.

The local meridional–vertical cross section further shows that the southerly anomaly over Southeast Asia in the dry phase blocked the cold air to penetrate southward (Fig. 6c). That is why the Southeast Asia remained a warm anomaly even though there was an extreme cold anomaly over central China in January (Fig. 5b). It is noted that the pattern of the moisture flux anomaly resembles that of the anomalous momentum flux shown in Fig. 6c and that the warm moist air was transported northward and upward at 30°N, with cold air beneath it. This vertical distribution might be responsible for the freezing rain in central China. Thus, the prolonged enhanced SH to the north and southerly anomalies induced by the dry phase of the ISO to the south might be responsible for the extreme cold anomaly over central and south China in late January. After the ISO phase shift, the cold anomaly was advected southward by the prolonged northerly anomaly over Southeast Asia (Fig. 6d).

![Fig. 5.](image)

**Table 1.** Correlation coefficients between the daily meridional wind (V) anomaly, daily temperature (T) anomaly, and the daily SH index for the whole winter (DJF). The meridional wind and temperature anomalies are averaged over the South China Sea (10°–25°N, 100°–120°E), and the SH index is defined as the averaged sea level pressure over 40°–60°N, 80°–120°E. As the daily data are not independent, we estimate the degree of freedom by calculating the effective sample as defined in Quenouille (1952), and the t test is used to determine the confidence level. Correlations significant at 95% (0.48) are marked in bold.

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![OLR Anomaly (15S-5N)](image)  ![1000hPa-T Ano (100E-120E)](image)

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**Fig. 5.** (a) The Hovmöller diagram for the daily OLR anomaly averaged over 15°S–5°N. The shading denotes the raw data and the contour represents the 20–70-day filtered anomalous OLR. The contour interval is 20 W m⁻². (b) As in (a), but for the unfiltered 1000-hPa temperature anomaly averaged over 100°–120°E. The boxes in (a) and (b) indicate the periods of the occurrence of the extreme cold anomaly. The brackets in (a) denote the periods of the negative OLR anomaly (wet phase) and positive OLR anomaly (dry phase) of Sumatra. The cold anomaly in the dry phase corresponds to the severe snow storm over central China that happened in mid-late January.
Figure 7 illustrates the evolution of key variables prior to and during the ECA event. Note that the time series of the convection (OLR) anomaly over Sumatra and the meridional wind and temperature anomalies over Southeast Asia resembled each other, and they are significantly correlated. The transition from a southerly anomaly to a northerly anomaly coincided well with the ISO phase change from a dry phase to a wet phase. This indicates that the tropical diabatic heating was responsible for the initiation of the northerly anomaly. It is emphasized that the SH was well established long before the wet phase of the ISO arrived at Sumatra. However, the cold air mass did not advance southward until the ISO switched into a wet phase because the southerly anomaly during the ISO dry phase prevented the cold air outbreak.

While the ISO convection was stalled over the Maritime Continent longitudes for an extended period (~30 days), it exhibited a significant meridional movement. Figure 8 shows a 2-day sequence of the low-level wind and OLR anomalies. On 8 February, maximum ISO convection was confined south of the equator over the Maritime Continent longitudes (Fig. 8a). The northerly anomaly induced by the convective heating led to a sequential cold and dry advection. The cold and dry air above the warm moist ocean surface may trigger the convective instability and thus new convection to the north of the original convection. The establishment of the convection north of the equator helped to reinforce the northerly anomaly during the ECA period.

5. Atmospheric response to ISO heating: Anomaly AGCM experiments

In this section, we will demonstrate that the prolonged northerly anomaly is forced by the tropical ISO convective heating based on AGCM experiments. The numerical strategy follows the early work of Simmons et al. (1983). An idealized diabatic heating based on the observation is prescribed to the anomaly AGCM to investigate the steady response of the atmosphere to the heating. As the ISO-induced heating moved eastward before it stayed at Sumatra, a series of numerical experiments with the same heating pattern but embedded...
in different locations was first conducted to reveal the optimal steady response to the heating sources. Below we focus on the discussion of the steady response to the heating over Sumatra.

The spatial distribution of the OLR anomaly in February 2008 exhibits an east–west dipole over the Indo-Pacific Ocean, with an enhanced convection in the Maritime Continent and a suppressed convection over the central Pacific (Fig. 9b). The amplitude of the OLR anomaly over Sumatra is about 60 W m\(^{-2}\), which corresponds to a peak heating rate of 3.5 K day\(^{-1}\) near 400 hPa as indicated by the Q1 profile (not shown; Yani et al. 1973). Based on the observations, an elliptic horizontal pattern of the heating (Fig. 10b) with a vertical profile as indicated in Q1 was prescribed in the anomaly AGCM.

The steady response of the low-level streamline shows a Gill-type circulation modified by the boreal winter mean flow. Over the equatorial belt, there are convergent zonal flows, with westerly (easterly) anomalies located to the west (east) of the heating center. Two cyclonic centers reside off the equator at each of hemispheres (Fig. 10b). Note that the anomalous cyclonic flows are not symmetric to the equator because of the asymmetry of the basic flow (Wang et al. 2003). A wavelike pattern appears along the subtropical jet, with an anticyclone anomaly in northern Indochina and a cyclone anomaly to the west of Taiwan. This zonal wavelike disturbance creates a strong zonal pressure gradient and thus generates a significant northerly anomaly over Southeast Asia. Compared to the observations (Fig. 10a), the simulation well reproduces the gross pattern of the observed circulation and demonstrates that the persistent northerly over Southeast Asia is indeed initiated and maintained by the diabatic heating anomaly over Sumatra. The major difference between the observation and the simulation lies in the underestimate of the northerly anomaly over the west edge of the Tibetan Plateau, Arabian Sea, and western Indian Ocean. We noted that the wind in the above regions can be simulated if the heating over the tropical Indian Ocean is specified.

When moving the heating northward to the South China Sea (5°N, 115°E), the circulation response resembles the steady response to the convection over Sumatra (not shown). This indicates the robustness of the model response, supporting the notion that the tropical ISO heating is responsible for the maintenance of the persistent northerly anomaly over Southeast Asia. The result above also implies that the amplitude of the northerly anomaly could be greatly enhanced when both the Sumatra and South China Sea heating sources are included.

6. Modulation of ISO by ENSO

A key question related to the ECA is why the large-scale convection associated with the ISO was stalled in
FIG. 8. The spatial evolution of the OLR anomaly (shading) and 850-hPa wind anomalies at day −4, day −2, and day 0 corresponding to the formation of subconvection [the arrow in (c)].
the Maritime Continent for a month or so and did not move eastward. In the following, we will demonstrate that it is the La Niña episode in the equatorial Pacific that prevented the eastward propagation of the ISO and led to the prolonged impact of the tropical heating on the northerly anomaly.

The distribution of the SSTA in February 2008 resembles a typical La Niña event; that is, a negative SSTA in the equatorial central and eastern Pacific and a positive SSTA extended from the northwestern Pacific to the north central Pacific (Fig. 9a). The Niño-3.4 time series shows that the SSTA reached a minimum (-1.8°C) in February 2008 (not shown), which was concurrent with the ECA. A narrow cold SSTA appeared along the East Asia coast. The occurrence of this cold anomaly was accompanied by the northerly anomaly and ECA and it persisted only for a month or so, suggesting that the cold SSTA can be attributed to the atmospheric forcing. As expected, the La Niña tended to suppress the convection over the equatorial eastern Pacific but enhance the convection over the Maritime Continent (Fig. 9b).

The Hovmöller diagram of the SSTA shows that the La Niña propagated westward from November 2007 to February 2008 at a speed of approximately 15° longitude per month (Fig. 11a). This westward-propagation characteristic is also found in the Hovmöller diagram of the OLR anomaly (Fig. 11b) and in the anomalous zonal wind fields (Fig. 12), indicating that the westward propagation might involve dynamic and thermodynamic air–sea coupling (Li and Philander 1996; Li 1997; Li and Hogan 1999). By early February, the maximum subsidence and easterly anomalies moved to the far western Pacific (150°–170°E) just next to the Maritime Continent (Figs. 11b and 12b). The westward shift of the suppressed convection and easterly anomalies prevented the ISO from penetrating farther eastward (Lin and Li 2008), and consequently the ISO stayed at the Maritime Continent longitudes. Thus, regarding its impact on the ECA, the La Niña has two effects. First, through its
westward progression, the cold episode blocked the eastward propagation of the ISO so that the heating over Maritime Continent has a prolonged impact on the circulation anomaly in Southeast Asia. Second, the La Niña enhanced the convection over the Maritime Continent through anomalous Walker circulation.

7. Conclusions and discussion

In this study we diagnose the unusual ECA over Southeast Asia in February 2008 by analyzing the NCAR–NCEP reanalysis, NOAA SST, and NOAA OLR data. The relative roles of the ENSO and ISO on the ECA are investigated. A series of anomaly AGCM experiments are further conducted to investigate the possible impact of the equatorial heating associated with the ISO on the ECA. The main results are summarized as below:

1) The ECA was accompanied by an enhanced prolonged SH and a persistent northerly anomaly over Southeast Asia. The former provided the persistent cold air outbreak and the latter was crucial to lead to a continuous cold advection.

2) The fluctuation of northerly and temperature anomalies associated with the ECA exhibited an intraseasonal period (~30 days), which was significantly correlated with the convection over Sumatra.

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**FIG. 10.** (a) Distributions of the observed 850-hPa streamline anomaly during the ISO wet phase (1–15 Feb). (b) Same as in (a) but for the steady response of the model to the elliptical heating (centered at 5°S, 115°E) marked by the gray contour. The thick gray arrows denote the northerly anomalies. The high (low) pressure anomaly is marked by H (L).
3) The onset of the northerly anomaly coincided with the arrival of the ISO convection at Sumatra. The phase of the northerly anomaly was coherent with the ISO phase of the convection over Sumatra; that is, the meridional wind anomaly switched from southe- rlies to northerlies as the ISO turned from a dry phase to a wet phase. The in-phase relationship between the northerly and convection anomalies suggests that the ISO heating was responsible for the initiation and the maintenance of the northerly anomaly over Southeast Asia. This hypothesis is further confirmed by the anomaly AGCM experiments.

4) The SST and circulation anomalies associated with the La Niña propagated westward at a speed of nearly 15° longitude per month and arrived in the far western Pacific by February 2008. The westward shift of the cold SSTA and anomalous subsidence prevented the ISO from propagating eastward so the ISO stayed over the Maritime Continent. This prolonged the influence of the tropical heating on the northerly anomaly, leading to the ECA.

The processes that caused the ECA are summarized in the schematic diagram presented in Fig. 13. A persistent blocking pattern of the upper-level height anomaly over Lake Baikal formed in mid-January 2008, which reinforced the SH by enhancing the climatological upper-level ridge upstream Lake Baikal (Takaya and Nakamura 2005). Though the SH was long persisting and record-breaking severe snow and ice storms occurred in central China in mid–late January, the cold air did not penetrate southward to Southeast Asia until the northerly anomaly was established. The northerly anomaly persisted for a month or so, and was significantly correlated with the ISO phase. In the ISO dry phase, the low-level wind anomalies over Southeast Asia was dominated by southerly anomalies, which did not allow for the cold air southward penetration. The southerly anomalies switched to northerly anomalies in response to the phase change of the ISO over Sumatra. As the northerly anomalies were initiated and maintained, the near-surface cold anomaly caused by the unusual severe snow/ice storms in central China was advected southward, leading to the ECA. The prolonged northerly anomaly can be attributed to the stationary ISO forcing over the Maritime Continent, as the westward-propagating La Niña blocked the ISO from moving eastward. As a result, the influence of the tropical heating prolonged the northerly anomaly over Southeast Asia. The persistent northerly anomaly continually swept the extratropical cold air southward and led to the ECA.

As shown in Fig. 9, a low-level east–west-oriented dipole was triggered in response to the tropical heating. The dipole-induced circulation anomaly generated a strong zonal pressure gradient and resulted in a strong northerly anomaly. Our sensitivity experiments indicate that the dipole-like disturbance is the optimal response to the tropical heating under the boreal winter.
3D mean flow. The diagnosis of kinetic energy conversion reveals that the disturbance gains energy from the mean flow (not shown). As the East Asian subtropical jet was enhanced by the anomalous local Hadley circulation, more available energy of the mean flow could be transported to the dipole-like disturbance. The low-level northerly might further strengthen the tropical heating by triggering the convective instability, as described in Fig. 9. Therefore, the tropical heating, the East Asian jet and the dipole-like disturbance might self-intensify through a positive feedback of the tropical–extratropical interaction.

The probability of occurrence of the ECA is rare in statistics. We particularly compared the ECA with the extreme cold event in 1968 (see Fig. 1c). The large-scale atmospheric circulation anomalies in 1968 were in general similar to those in 2008. For example, a south–north-oriented dipole-like surface temperature anomaly appeared over Eurasia, and a blocking height over upper Lake Bakial and a strengthened SH were clearly observed. In addition, a significant cold SSTA was found in the equatorial eastern Pacific. The major difference between 1968 and 2008 is that the cold Pacific SST anomaly was approximately stationary in 1968, whereas it moved westward along the equator in 2008. Only the coincidence of the prolonged enhanced SH, the tropical ISO, and the La Niña episode together may lead to the unusual ECA. The understanding of the ECA is not only of scientific
interest but also practically useful for the extended weather prediction, such as the forecasting of a cold surge with an extended period. The fact that the initiation of the northerly anomaly over Southeast Asia was concurrent with the arrival of an ISO at the Maritime Continent suggests that the monitoring of tropical heating is particularly important for the prediction of severe cold air outbreaks. The close phase relationship between the wind anomaly and the ISO also suggests that the ISO prediction is essential for improving the predictability of the low-frequency variability of the EAWM.

This study focuses on the impact of the ISO-related tropical heating on the ECA. Our conclusions do not exclude the possible contributions from the midlatitude or high-latitude processes. So far it is not clear how the upper-level height anomaly over Lake Baikal was maintained for a quite long period. A significant Arctic Oscillation (AO) is identified during the ECA. Whether or not the unusually strong SH was related to the AO requires further investigation.

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