A Revisit of the Tropical-midlatitude Interaction in East Asia Caused by Cold Surges

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Abstract

A short-wave train emanating from the Southeast Asian tropics which links interannual variations of the winter climate systems in both East Asia and North America was identified recently. This short-wave train may affect the activity of cold-surge disturbances over the eastern seaboard of East Asia, and the northwestern Pacific. The interaction between cold surges and the planetary-scale winter monsoon circulation in East Asia, was extensively explored after the Winter Monsoon Experiment (WMONEX). However, the finding of the North-Pacific short-wave train motivates us to revisit three aspects of the East-Asian circulation related to cold surges, with an emphasis on the effect of the wave activity in East Asia. First, the well-developed local Hadley circulation coupled with the East-Asian stationary waves and tropical troughs facilitates the interaction between cold surges, and planetary-scale circulation in East Asia. Second, the intensification of the East-Asian jet following cold surges is attributed to the ridge amplification/trough deepening of the East-Asian stationary waves by the cold-surge disturbances. Finally, the downward branch of the local Hadley circulation in East Asia provides the large-scale vortex compression, which enhances the development of cold-surge disturbances along the east coast of Northeast Asia.

1. Introduction

The cold surge is one of the most important and researched winter monsoon phenomena in East and Southeast Asia. After the Winter Monsoon Experiment (WMONEX, Greenfield and Krishnamurti 1979), numerous studies were made to explore various aspects of cold surges in the context of the planetary-scale winter monsoon (Lau and Li 1984; Lau and Chang 1987),[1] particularly the role played by cold surges in the tropical-midlatitude interaction. For example, the intensification of the local Hadley circulation in East Asia following the occurrence of a cold surge, may accelerate

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[1] Excellent reviews of these studies have been offered by Lau and Li (1984) and Lau and Chang (1987). Perhaps, it would be too lengthy in this paper to provide all pertaining references of the East-Asian cold surge research. However, readers are referred to these review papers for previous works in this area.

the East-Asian jet (Chang and Lau 1980) and induce a midlatitude short-wave train in the North Pacific (Lau et al. 1983). Because of the public concern of monsoon rain, the major recent research attention of the East Asian monsoon was focused on the summer season (e.g., the South-China Sea Monsoon Experiment (Lau et al. 2000)). As pointed out by Cheang (1987), the winter monsoon brings the Southeast Asian countries south of 10°N about 50% of their annual rainfall. In addition to rainfall, cold surges often create hazardous weather conditions in East Asia (Chen et al. 2002). In view of the affects of cold surges on weather and climate, the winter monsoon is equally as important as the summer monsoon in these regions.

In addition to the Pacific-North America (PNA) teleconnection pattern (Wallace and Gutzler 1981; Horel and Wallace 1981), Chen (2002) recently identified a short-wave train emanating from Southeast Asia during the extreme phases of the ENSO cycle. Across the North Pacific along its rim, this short-wave train provides a link between the East-Asian winter monsoon and the North-American winter climate system. The North American winter climate is affected not only by the classic PNA wave train, but also by the North Pacific short-wave train. Chen's finding echoes Yang et al.'s (2002) argument about the possible link of the Asian-Pacific-American winter climate anomalies through the East-Asian jet. On the other hand, Zhang et al. (1997) showed that the cold surge activity over East Asia undergoes a distinct interannual variation in accordance with the ENSO cycle. The activity of cold-surge disturbances over the region between Northeast Asia, and the northwestern Pacific, may be affected by this short-wave train. In order to prepare for this possible new research direction, we revisit the relationship between the cold surge and the planetary-scale winter monsoon circulation developed by the post WMOEX research.

Three aspects of the interaction between cold surge, and the planetary-scale monsoon are particularly of interest in this study:

1) Regardless of the difference between their horizontal scales, the winter circulation systems in East Asia and North America have some similarities in their structure: over the continent an upper-level, east-coast trough is coupled with a low-level anticyclone. Cold surges therefore occur over both continents. It was shown by Chang and Lau (1980) that a strong, and well-organized interaction exists between the East-Asian cold surge, and the upper-level jet. In contrast, this type of tropical-midlatitude interaction does not seem to occur in North America, as revealed from extensive analyses of the North American cold surges conducted by some previous studies (e.g., Colle and Mass 1995; Schultz et al. 1997). *Is there any unique feature of the planetary-scale winter circulation in East Asia to make this interaction more effectively there?*
2) Based on the confluence theory (Namias and Clapp 1947), Blackmon et al. (1977) argued that subtropical jets are maintained through the acceleration (deceleration) of the Coriolis force, induced by the transverse circulation at the entrance (exit) region. On the other hand, Krishnamurti (1979) suggested that the maintenance of the three subtropical jet streams in the winter Northern Hemisphere may be related to the rainfall centers over the three tropical continents through the planetary-scale divergent circulation. This suggestion was substantiated by Chen et al. (1988). The local Hadley circulation in East Asia is a part of the planetary divergent circulation, and may be intensified by the tropical convection stimulated by cold surges. As inferred from these subtropical jet maintenance mechanism, the East Asian jet may be accelerated by the intensified East-Asian Hadley circulation following cold surges (e.g., Chang and Lau 1980). Since the jet is located ahead of the east-coast trough, its speed may be increased by the *deepening* of this trough (because of the enhancement of horizontal streamfunction gradients). Chang and Lum (1985) suggested that the intensification of the East Asian jet, following East Asian cold surges, may cause midlatitude baroclinic development, rather than by the Coriolis acceleration. *Can the intensification of the East-Asian jet stream following the amplification (deepening) of the east-coast trough, be caused by the perturbation of cold-surge disturbances?*

3) The short-wave train associated with the East-Asian cold surge usually propagates eastward from Central Eurasia (Joung and Hitchman 1983). Lau et al. (1983) suggested that the development of midlatitude synoptic disturbances may be influenced by the East-Asian Hadley circulation, which is intensified by cold surges. Although Lau and Lau (1984) depicted the structure, and presented the energetics analysis of these perturbations; it was pointed out by Lau and Li (1984) that the physical mechanism for such an influence (as Lau et al. (1983) suggested) was not well understood, even today. However, *it is unclear how the synoptic-scale cold-surge disturbances interact with the intensified local Hadley circulation.*

It is not our intent in this study to provide an extensive analysis for all three questions raised above. Instead, we would only like to offer some heuristic argument, or suggestive answers, to these questions with a planetary wave perspective. Since the reanalysis data generated by several operational centers have become available recently, new interest in exploring East-Asian cold surges, and their interaction with the planetary-scale monsoon circulation, will be hopefully revived.

2. Case selection

In different studies, a cold surge is often identified by different criteria. For example, the following three criteria were used by Lau and Chang (1987) in their previous studies to define the cold-surge onset within a 24–48 h period:

1) Surface temperature (T_s) drop at Hong Kong $\geq 5°\mathrm{C}$,
2) Surface pressure (p_s) gradient between coastal and central China ≥ 5 mb, and
3) prevailing northerlies over the South China Sea $\geq 5\ \mathrm{ms}^{-1}$.

Examining the interannual variation of the cold surge activity in East Asia, Zhang et al. (1997) later adopted a different approach:

1) Onset of a cold surge: A surface anticyclone appears in the Mongolia region with its center $p_s \geq 1035$ mb. During a 24–48 h period, the T_s drop $\geq 9°\mathrm{C}$ occurs in central China, and $\geq 6°\mathrm{C}$ in Southeast China.
2) Demise of a cold surge: At the center of a surface anticyclone, p_s becomes smaller than 1024 mb, and a negative p_s tendency lasts for 24 h. In addition, a positive T_s trend appears over a half area of East Asia.

These two sets of criteria share some common features: appearance of a surface anticyclone in East Asia, with strong northerlies spiraling out of the continent, and a p_s rise accompanied with a T_s drop. Some differences exist between them. Cold surges identified by Lau and Chang's criteria penetrate the deep tropics, while those identified by Zhang's criteria include all disturbances generated by the Siberian high. However, we are interested only in the former surges. Therefore, some other features should be included in our case selection: intensification of the local Hadley circulation in East Asia, and enhancement of cumulus convection in tropical Southeast Asia. The winter Hadley circulation may cover a latitudinal zone of 10°S–30°N (e.g., James 1994). In order to clearly illustrate the tropical-midlatitude interaction through the local Hadley circulation, we shall identify strong cold surges with the following constraints of meteorological variables at Singapore, in addition to Lau and Chang's criteria,

1) At the surface, $\Delta p_s > 0$, $\Delta T_s < 0$, and $\Delta|\boldsymbol{V}_s| > 0$ (with prevailing northerlies) over a 24–48 hr period, (where $\Delta(\ ) \equiv (\ )(t + 24\ \mathrm{hr}) - (\ )(t)$),
2) A cold surge (reaching Singapore) is well depicted by the surface streamline chart. The cumulus convection induced by a cold surge is well defined by OLR $\leq 200\ \mathrm{wm}^{-2}$ in tropical Southeast Asia.
3) A well-developed local Hadley circulation, portrayed by $(v_D, -\omega)$ (115°E) (where v_D is the divergent component of meridional wind), covers at minimum the latitudinal zone of 10°S–30°N.

The NCEP/NCAR reanalysis data (Kalnay et al. 1996), and the outgoing longwave radiation (OLR) data for six winters (1992–1998), are used for analysis in this study. The major results in this study are presented based upon the composite charts of all selected cold surges at their *peak* phases. Shown in Fig. 1 is a case (February 9, 1996) of the East-Asian cold surge randomly selected as an example in our identi-

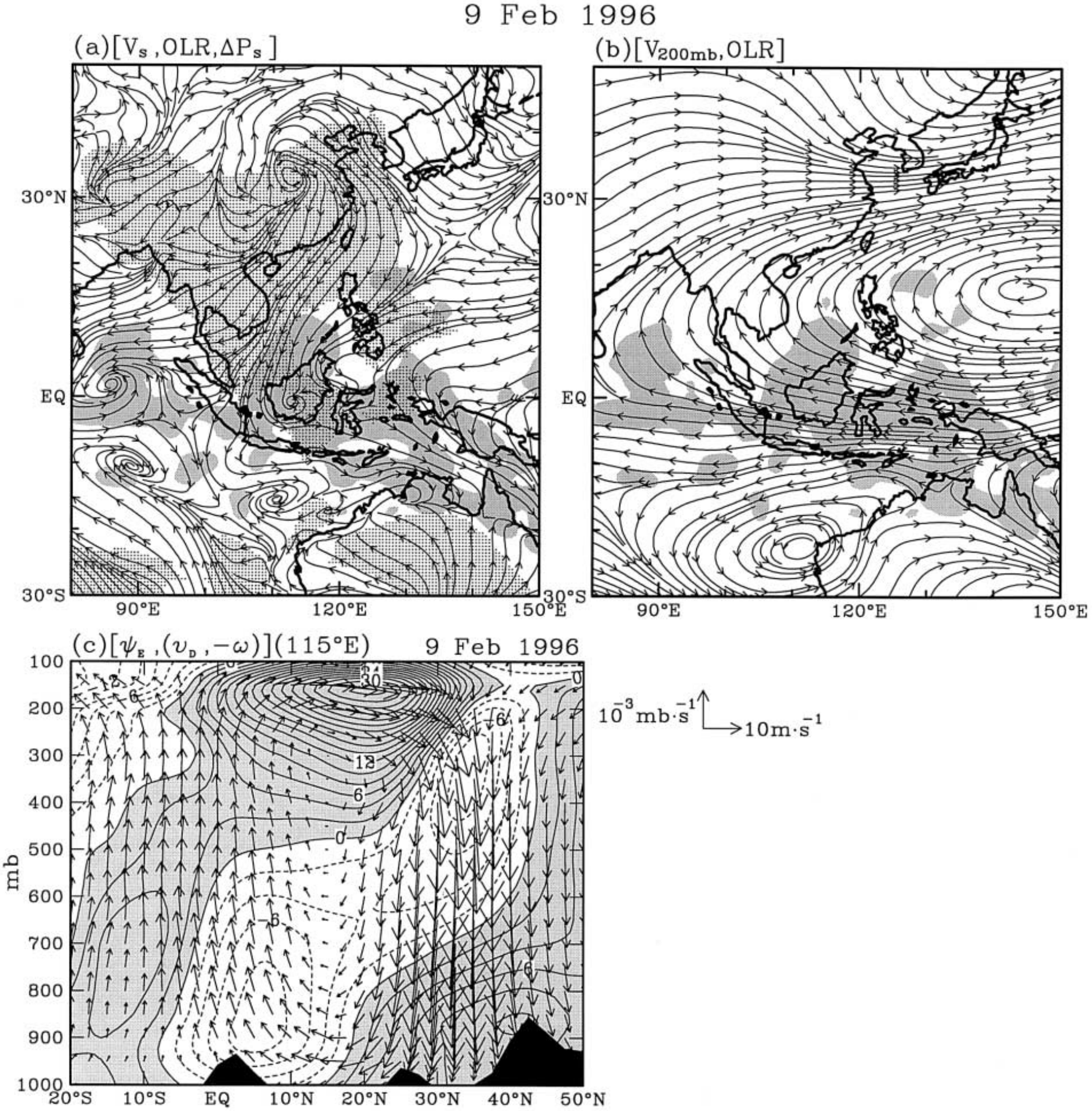

Fig. 1. The cold surge of February 9, 1996 depicted by (a) the surface streamline chart ($\boldsymbol{V}_s$) superimposed with OLR ($\leq$200 wm^{-2}; heavily stippled areas) and Δp_s ($\leq$0.5 mb/24 hr; surface pressure tendency over a 24 h period; dotted areas), (b) the 200-mb streamline chart [$\boldsymbol{V}$ (200 mb)] superimposed with OLR ($\leq$200 wm^{-2}), and (c) the local Hadley circulation ($v_D, -\omega$) (115°E) superimposed with the vertical cross-section of eddy streamfunction ψ_E (115°E). The contour interval of ψ_E (115°E) is 2×10^6 m^{2}s^{-1}; positive values of ψ_E (115°E) are stippled.

fication. As indicated by surface streamlines, and the 24 hr-surface pressure tendency, (areas of $\Delta p_s \geq 0.5$ mb/24 hr are dotted) in Fig. 1a, the cold-air mass following the cold surge moves southward all the way to the tropical region between the southern Bay of Bengal, Bornea, and northern Australia. Over the former two regions, cumulus convection (indicated by OLR $\leq$ 200 wm^{-2}; heavy shaded area) was induced, and two monsoon vortices were formed

Table 1. Dates (month/day/year) of the selected cold surges which satisfy criteria set in Section 2.

year	92/93	93/94	94/95	95/96	96/97	97/98
dates	12/10/92	12/16/93	12/20/94	12/04/95	12/06/96	12/09/97
	12/28/92	12/22/93	01/12/95	12/16/95	12/27/96	12/10/97
	01/25/93	01/06/94	01/29/95	01/22/96	01/25/97	12/12/97
	02/01/93	01/22/94	02/01/95	02/02/96	02/18/97	01/04/98
	02/17/93	01/26/94	02/04/95	02/09/96		01/18/98

by the cold surge. The contrast between the $\boldsymbol{V}_s$ and $\boldsymbol{V}$ (200 mb) (Fig. 1b) streamline charts reveals that the cold surge is overlaid by a well-developed *upper-level anticyclone* which separates the East-Asian jet (indicated by crowded streamlines), and the east-coast trough, from the upper-level tropical easterlies along the equator. The local Hadley circulation associated with the cold surge is depicted by the vertical cross-section of $(v_D, -\omega)$ (115°E) (Fig. 1c). This circulation is driven by tropical cumulus convection; maintained by the upward motion over the tropical low pressure and coupled with the sinking cold air over the subtropical high pressure. The north-south surface pressure gradients, which are reflected by positive $\Delta\psi_E$ (115°E) anomalies in higher latitudes, and negative $\Delta\psi_E$ (115°E) anomalies in the tropics, are conducive to the occurrence of a cold surge. Additionally, the upper-level anticyclone (indicated by a positive $\Delta\psi_E$ (115°E) cell centered at 20°N) blocks the southward advection of cold air in the upper troposphere, but facilitates a cold surge in the lower troposphere.

Following the case shown in Fig. 1, and the criteria developed above, 29 cases were identified for the 1992–1998 period, and used to illustrate the tropical-midlatitude interaction by cold surges. Dates of maximum intensity of these selected cases are listed in Table 1.

3. Results and discussion

3.1 Why is the East-Asian cold surge more effective in causing the tropical-midlatitude interaction?

The major features of winter time stationary waves depicted by Lau (1979; his Figs. 1 and 2) are characterized by a horizontal phase reversal at 30°N, a westward vertical tilt north of 30°N and maximum amplitudes near the tropopause in low and middle latitudes. These characteristics of stationary waves in middle and high latitudes are revealed from the three-dimensional structure of stationary waves depicted by seasonal-mean eddy streamfunction ($\bar{\psi}_E$) during the northern winter (December–February), shown in Fig. 2. The midlatitude troughs (negative $\bar{\psi}_E$ anomalies in Fig. 2a) are located over the eastern part of two major landmasses, while the midlatitude ridges (positive $\Delta\psi_E$ anomalies in Fig. 2a) are found over the eastern oceans and Central Eurasia. In the lower troposphere (Fig. 2b), the Siberian high in East Asia is juxtaposed with the Aleutian low, while the Pacific Northwest anticyclone is aligned with the Icelandic low. As mentioned previously, the midlatitude high-low contrasts over the two major continents are very much *alike*, regardless of their horizontal scales.

White (1982; his Fig. 2b) showed that summertime stationary waves in the tropics exhibit a monsoonal characteristic of vertical phase reversal. Although Lau's (1979; his Fig. 2b) vertical cross-section of eddy geopotential height in low latitudes does not reveal such a monsoonal feature, one can find this vertical phase reversal of tropical stationary waves in tropical $\bar{\psi}_E$ (Fig. 2d). Unlike midlatitudes, the tropical stationary waves are primarily formed by the wave 1 component embedded by planetary waves of smaller scales. For the eastern hemisphere, the Australian monsoon trough and surface low pressure south of the Eurasian continental high are overlaid by the East-Asian anticyclone and the East African high. In the western hemisphere, the two oceanic anticyclones over the eastern Pacific and the north Atlantic are covered by two oceanic troughs aloft. Evidently, the spatial structure of the tropical stationary waves in these two hemispheres are out of phase.

Because of the structure difference of tropical stationary waves between Southeast Asia and Central America, the responses of regional circulation in these two regions to the southward intrusion of cold air mass may be different. As inferred from $\bar{\psi}_E$ (850 mb) in Fig. 2b, or the contrast between $\bar{\psi}_E$ (50°N) (Fig. 2c) and $\bar{\psi}_E$ (10°N) (Fig. 2d), the pressure gradients between the Siberian high, and the tropical low pressure (including the Australian monsoon trough and the South-Asian continental surface

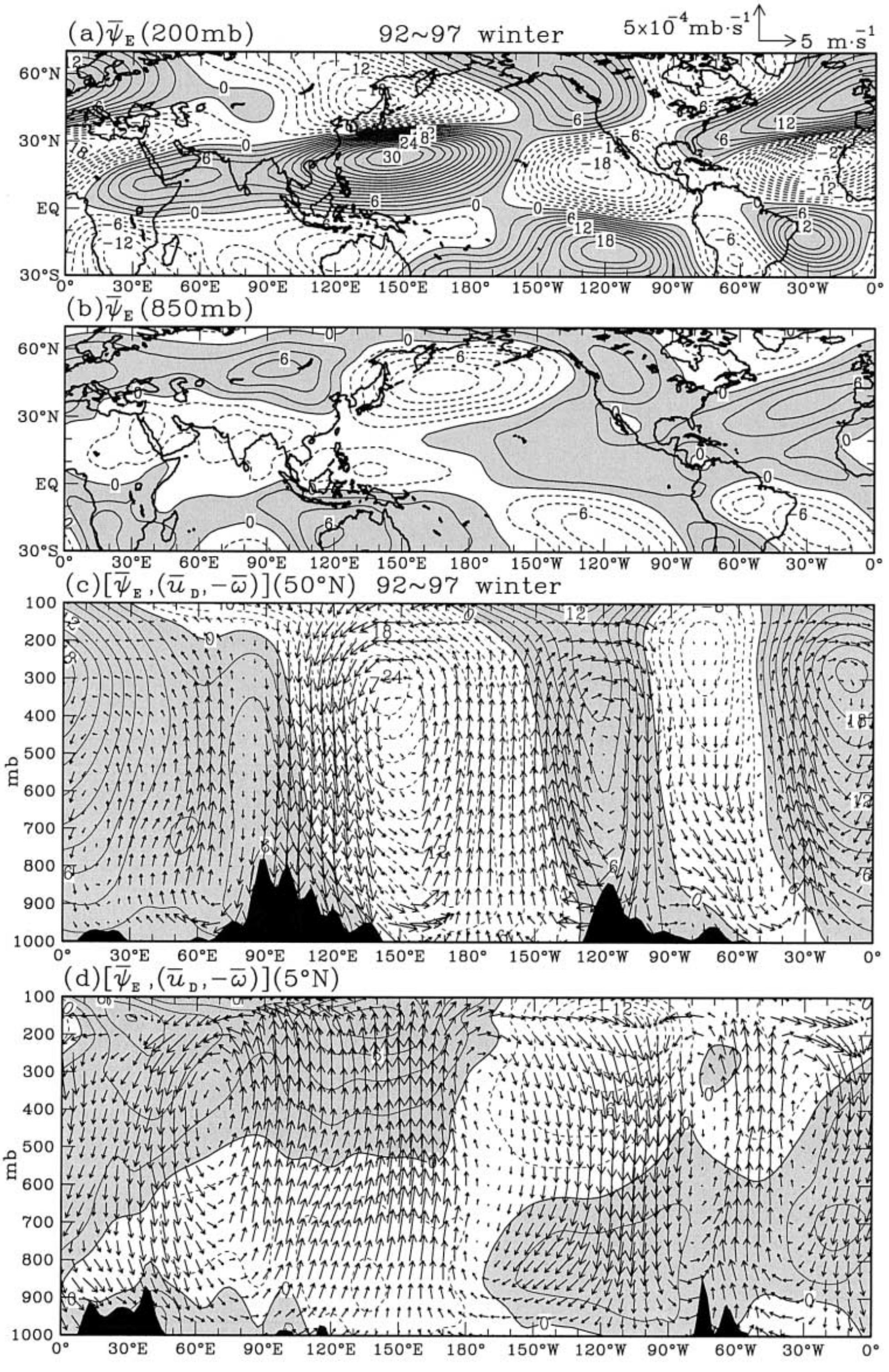

Fig. 2. Structure of wintertime stationary waves in the Northern Hemisphere depicted by eddy streamfunction ($\bar{\psi}_E$) superimposed with the east-west circulation ($\bar{u}_D, -\bar{\omega}$): (a) $\bar{\psi}_E$ (200 mb), (b) $\bar{\psi}_E$ (850 mb), (c) the vertical-longitude cross-section of stationary eddy and the east-west circulation at 50°N, [$\bar{\psi}_E, (\bar{u}_D, -\bar{\omega})$] (50°N), and (d) same as (c) except at 10°N, [$\bar{\psi}_E, (\bar{u}_D, -\bar{\omega})$] (10°N). The contour interval of $\bar{\psi}_E$ is 2×10^6 m^2 s^{-1}; positive values of $\bar{\psi}_E$ are stippled.

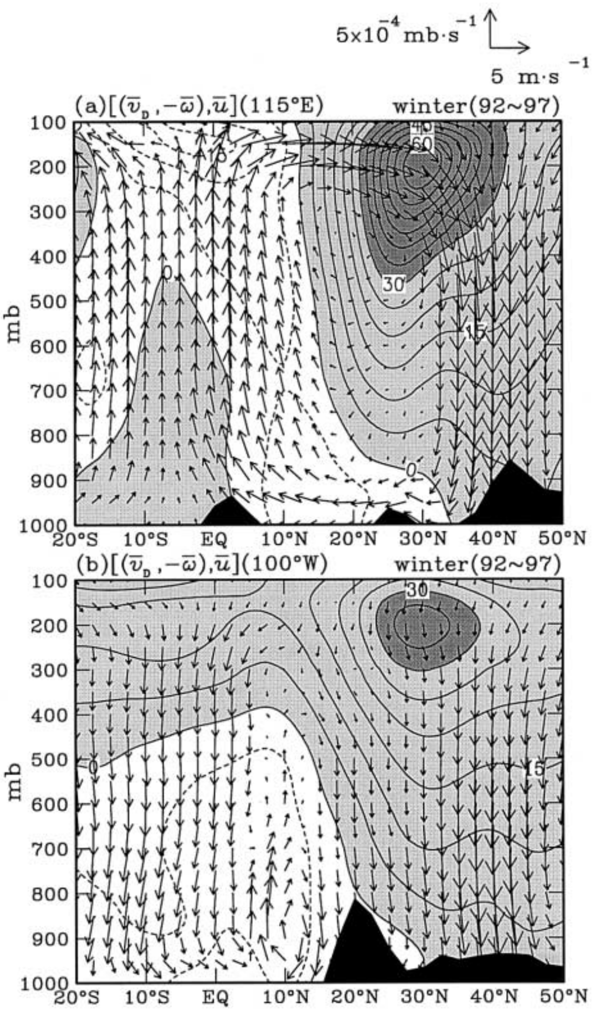

Fig. 3. Wintertime local Hadley circulation $(\bar{v}_D, -\bar{\omega})$ superimposed with the wintertime local zonal wind $(\bar{u})$: (a) $[(\bar{v}_D, -\bar{\omega}), \bar{u}]$ (115°E) in East Asia and (b) $[(v_D, -\bar{\omega}), \bar{u}]$ (100°W) in North America. The contour interval of u is 5 ms^{-1}; values of $u > 0$ ms^{-1} (>30 ms^{-1}) are lightly (heavily) stippled.

low pressure), may facilitate the cold-air outflow from Siberia to sweep equatorward across East and Southeast Asia, and often reach the equator and the Australian monsoon region. In contrast, the southward sweeping cold air from Canada across the central United States may be hindered by the westward extended North Atlantic high. In the upper troposphere (Fig. 2a), the East Asian anticyclone blocks the southward cold-air advection, so that this advection can only occur underneath this high system. In other words, the southward cold-air advection is confined in the lower troposphere. On the contrary, the western European high does not extend sufficiently westward in the upper troposphere to prevent the cold air advection southward in North America. Thus, the cold air in the central United States may be advected over the entire depth of the troposphere. The southward cold-air advection is accompanied by the descending motions ahead of the midlatitude ridges, for example, over 90°E–120°E and 110°W–90°W (Fig. 2c). In response (revealed from Fig. 2d), there are tropical ascending motions over the southeast-Asian longitudes (110°E–160°E), but not over the American longitudes (110°W–80°W). As shown in Fig. 3, the descending motions in midlatitudes, and the ascending motions in the tropics, form a well-developed local Hadley circulation in East Asia (as shown in Fig. 3a), and a much weaker and less organized one with smaller north-south extent over North America (Fig. 3b). It is inferred from the differences in their meridional scale and intensity that the local Hadley circulation in East Asia is more conducive to the tropical-midlatitude interaction during cold surges (stressed by Lau and Chang (1987)) than that in North America.

3.2 *How is the East-Asian jet intensified by cold surges?*

As shown in Fig. 2c, cold air sinks ahead of the midlatitude ridge (or the rear of the midlatitude trough), and spreads southward to the tropics to induce cumulus convection there. The midlatitude descending motion, and the tropical ascending motion, thus form the East-Asian local Hadley circulation depicted by the vertical cross-section of $(v_D, -\omega)$ (115°E) in Fig. 3a. The vertical cross-section of u (115°E), superimposed in this figure, clearly shows that the entrance region of the East-Asian jet (maximum u (115°E)) is located close to the top of the downward branch of the local Hadley cell, instead of the upper southerly branch shown in Blackmon et al.'s (1977; their Fig. 5a) schematic diagram of the local Hadley circulation, and the location of the jet. It is inferred from Fig. 2a that the East-Asian jet is basically formed by the large north-south gradients of streamfunction straddling the East-Asian anticyclone in the tropics-subtropics, and the East-Asian trough in midlatitudes.

The East-Asian jet can be intensified because of the amplification of stationary waves over East Asia and its adjacent ocean, and the ridge amplification/trough deepening in East Asia. What may be the possible mechanism to amplify the East-Asian stationary waves? It was shown by Lau and Lau (1984), and will also be shown in the next subsection, that the occurrence of a cold surge is always accompanied by an eastward-propagating dipole (a ridge in the west and a trough in the east) of synoptic-scale disturbances. The midlatitude stationary waves in East Asia and the adjacent ocean (with a ridge over the continental landmass and a trough over the eastern seaboard; Fig. 2a) can be perturbed by these cold-surge dipole disturbances. In the meantime, the East-Asian local Hadley circulation can be intensified by the amplification of the East-Asian stationary waves, which in turn strengthens the coupling between the midlatitude (ridge/trough) and the tropical (East-Asian anticyclone/Australian monsoon trough) stationary waves.

The composite cold-surge departures of the local Hadley circulation, $\Delta(v_D, -\omega)$ (115°E), and zonal wind, Δu (115°E), from their long-term, winter-mean cross-sections are displayed in Fig. 4a. Two possible effects on the regional circulation caused by the cold-surge dipole disturbances may be inferred from this figure. 1) Because the local Hadley circulations and its perturbation induced by cold surges depicted by $(v_D, -\omega)$ (115°E) (Fig. 3a) and $\Delta(v_D, -\omega)$ (115°E) (Fig. 4a) respectively, exhibit the same direction, this local secondary circulation in East Asia is evidently intensified by cold surges. 2) The positive Δu (115°E) centered at 250 mb, slightly north of 30°N, manifests the intensification of the East-Asian jet following the amplification of the stationary waves (ridge/trough) over East Asia (perhaps by the dipole of cold-surge disturbances which will be illustrated in the next subsection). The second effect differs from the conclusion of previous studies summarized by Lau and Chang (1987) that the East-Asian jet can be accelerated by the Coriolis force induced by the upper southerly branch of the local Hadley circulation.

The East-Asian stationary trough is planetary-scale, but the cold-surge disturbances are only synoptic scale. Can we ignore the contribution from the planetary-scale waves? In order to clarify this question, a scale separation is introduced: waves 1–2 and 3–15 are considered as the planetary- and synoptic-scale regimes, respectively. The latter wave regime is designated by $(\ )^S$. Contributions to the local Hadley circulation, and the East-Asian jet by the short-wave regime, are shown in Fig. 4b.

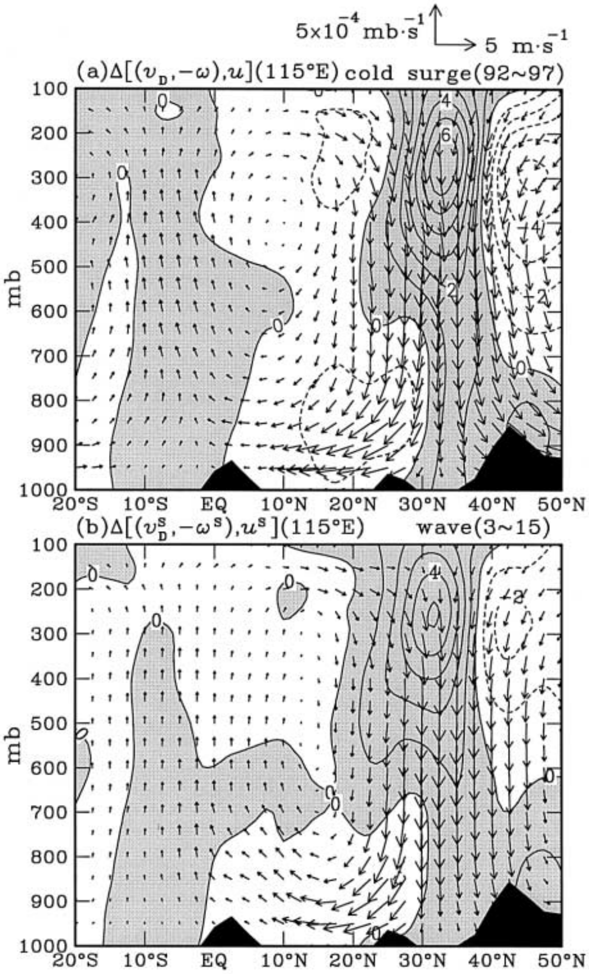

Fig. 4. (a) Departures of the composite East-Asian local Hadley circulation and zonal wind (of all selected cold surges) from their climatologies shown in Fig. 3a, $\Delta[(\bar{v}_D, -\bar{\omega}), \bar{u}]$ (115°E), and (b) $\Delta[(v_D^S, -\omega^S)]$ (115°E), contribution to $\Delta[(\bar{v}_D, -\bar{\omega}), \bar{u}]$ (115°E) from the short-wave (waves 3–15) regime. The contour intervals of Δu (115°E) is 1 ms^{-1}; values of Δu (115°E) > 0 ms^{-1} are stippled.

The comparison between Figs. 4a and 4b clearly indicates that the effect on the regional circulation by cold surges is largely caused by the synoptic-scale cold-surge disturbances.

3.3 *How does the tropical-midlatitude interaction induced by cold surges affect the surge ensuing disturbances?*

As shown in Section 3.2, the local Hadley circulation in East Asia may be intensified by the southward sweeping cold air accompanying the amplification of East-Asian stationary waves and cold surges. In addition to the midlatitude process, this circulation may also be intensified by the enhancement of tropical cumulus convection induced by cold surge. Chang and Lau (1980, their Fig. 14) argued that cold surges stimulate the tropical-midlatitude interaction: the acceleration of the East-Asian jet through the Coriolis force induced by the upper southerly branch of the local Hadley circulation. In contrast, the East-Asian jet may mainly be intensified by the amplification of the short-wave regime over East Asia as shown in Fig. 4. Joung and Hitchman (1982, their Fig. 2) found that the ridge/trough dipoles of the short-wave train associated with strong cold-air outbreaks are almost located at about the same position during the same temporal phases of these synoptic disturbances in East Asia. Analyzing the energy budget, Lau and Lau (1984) showed that the evolution of the cold-surge disturbances does not differ from that of the midlatitude synoptic disturbances along the storm track. Results obtained by these studies led to the following question: in addition to the interaction between the local Hadley circulation and the East Asian jet, can the tropical-midlatitude interaction be established between the local Hadley cell and the cold-surge disturbances?

If the tropical-midlatitude interaction can be established between the local Hadley circulation and the cold-surge disturbances, how do they interact? This interaction may not be easily illustrated by the open-domain energy budget analyzed by Lau and Lau (1984). Lau and Holopainen (1984) examined the maintenance of synoptic disturbances in midlatitudes with a simplified quasi-geostrophic tendency equation, which includes the vertical differentiation of vorticity advection, and the divergence of sensible heat advection. It is perhaps difficult, if not impossible, to use this tendency equation to deal with the interaction. To explore the possible mechanism of propagating monsoon depressions westward against the monsoon westerlies, Sanders (1984) introduced the quasi-geostrophic streamfunction budget equation with which he was able to show the evolution of the streamfunction perturbation following the development of the monsoon depression's secondary circulation. The cold-surge disturbances can be well depicted by streamfunction (ψ) perturbations, while the local Hadley circulation and the divergent circulation associated with the cold-surge disturbances can be portrayed by velocity potential (χ) perturbations. With these two variables, the streamfunction budget equation (i.e., the inverse Laplace transform of the vorticity equation) is a natural diagnostic means to demonstrate the possible tropical-midlatitude interaction. Following Sanders (1984), the quasi-geostrophic streamfunction budget equation may be written as:

$$\underset{\psi_t}{\frac{\partial\psi}{\partial t}} = \underset{\psi_A}{\nabla^{-2}[-\boldsymbol{V}\cdot\nabla(\zeta+f)]} + \underset{\psi_{\chi 1}}{\nabla^{-2}(-f\nabla\cdot\boldsymbol{V})}. \tag{1}$$

Separating the atmospheric flow into zonal $(\ )_Z$, and wave components in different wave regimes, we may write the linearized Eq. (1) in the following form for a short-wave (waves 3–15) regime:

$$\underset{\psi_t^S}{\frac{\partial\psi^S}{\partial t}} = \nabla^{-2}\left(\underset{\psi_{A1}^S}{-u_Z\frac{\partial\zeta^S}{\partial x}} \underset{\psi_{A2}^S}{-v^S\beta}\right) + \underset{\psi_{x1}^S}{\nabla^{-2}(-f\nabla\cdot\boldsymbol{V}^S)}. \tag{2}$$

A disturbance depicted by ψ^S is primarily maintained by the counteraction between the two dynamic processes: the streamfunction tendencies induced by the vorticity advection ($\psi_{A1}^S+\psi_{A2}^S$), and by the vorticity generation/destruction (caused by the stretching/compression of planetary vorticity). The latter process provides a mechanism for the divergent flow to interact with the rotational flow.

The composite streamfunction departures ($\Delta\psi^S$) (of all selected cold surges listed in Table 1) from the climatological-mean values in the short-wave regime are shown in Fig. 5. A well-organized short-wave train emanating from

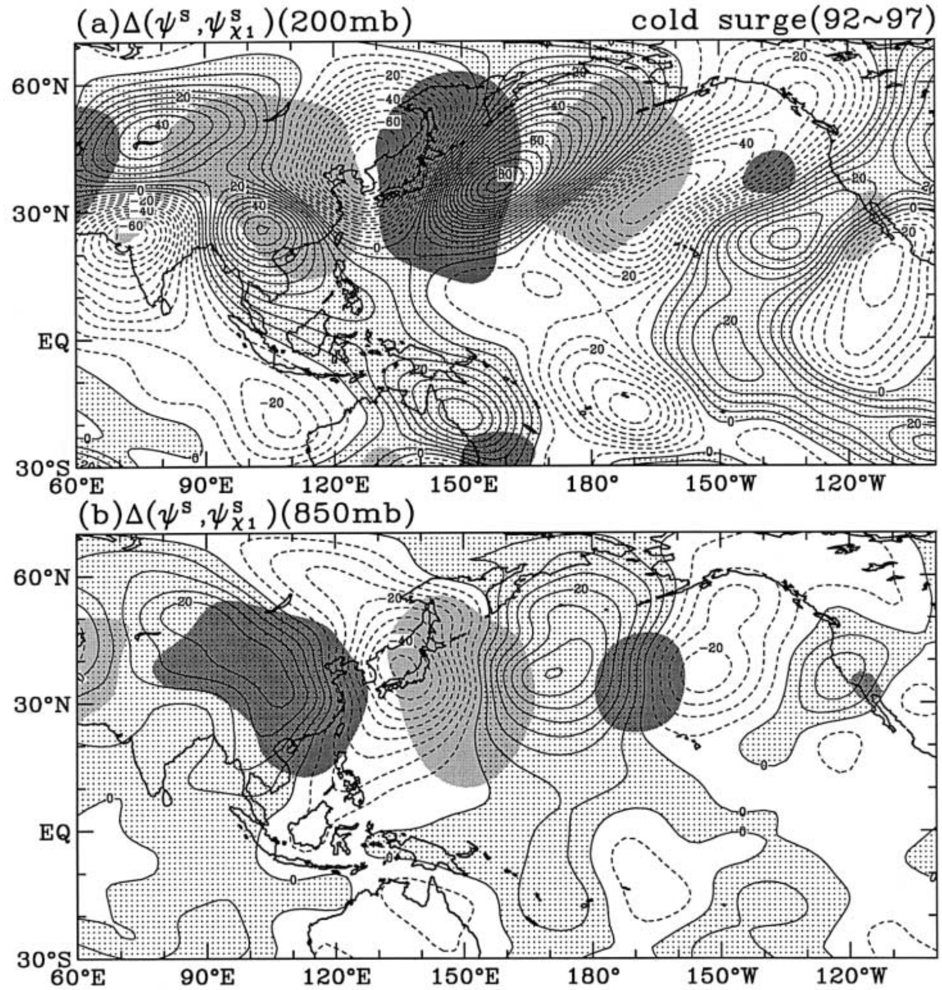

Fig. 5. Departures of composite streamfunction and streamfunction tendency induced by vortex stretching (of all selected cold surges) in the short-wave regime from their climatologies (not shown); (a) $\Delta(\psi^S, \psi^S_{\chi1})$ (200 mb) and (b) $\Delta(\psi^S, \psi^S_{\chi1})$ (850 mb). The contour interval of $\Delta\psi^S$ is 5×10^5 m^{2}s^{-1}; positive values of $\Delta\psi^S$ are dotted. Values of $\Delta\psi^S_{\chi1} > 30$ m^{2}s^{-2} (<-30 m^{2}s^{-2}) are heavily (moderately) stippled.

Eurasia clearly stands out with a positive cell (corresponding to a ridge), and a negative cell (corresponding to a trough) located in Northeast Asia. This short-wave train resembles those depicted by Joung and Hitchman (1982) with strong cold-air outbreaks, and by Lau and Lau (1984) with cold surges of WMONEX. The corresponding composite velocity potential departures ($\Delta\chi^S$) are displayed in Fig. 6. The contrast between $\Delta\psi^S$ and $\Delta\chi^S$ reveals some features of these two anomaly fields important to the tropical-midlatitude interaction: 1) A spatial quadrature relationship exists between $\Delta\psi^S$ and $\Delta\chi^S$, and 2) The comparison between $\Delta(v^S_D, -\omega^S)$ (Fig. 4b) and $(\boldsymbol{V}^S_D, \chi^S)$ (Fig. 6), indicates that the intensification of the local Hadley circulation by cold surges is mostly attributed to the $\Delta\chi^S$ cells centered over East Asia in midlatitudes, and Indonesia in the tropics. Thus, the interaction between perturbations depicted by the $\Delta\chi^S$ and $\Delta\psi^S$ fields may be used to illustrate the coupling of the local Hadley circulation with the cold-surge disturbances.

Based upon Figs. 5 and 6, let us express both $\Delta\psi^S$ and $\Delta\chi^S$ in terms of simple sinusoidal

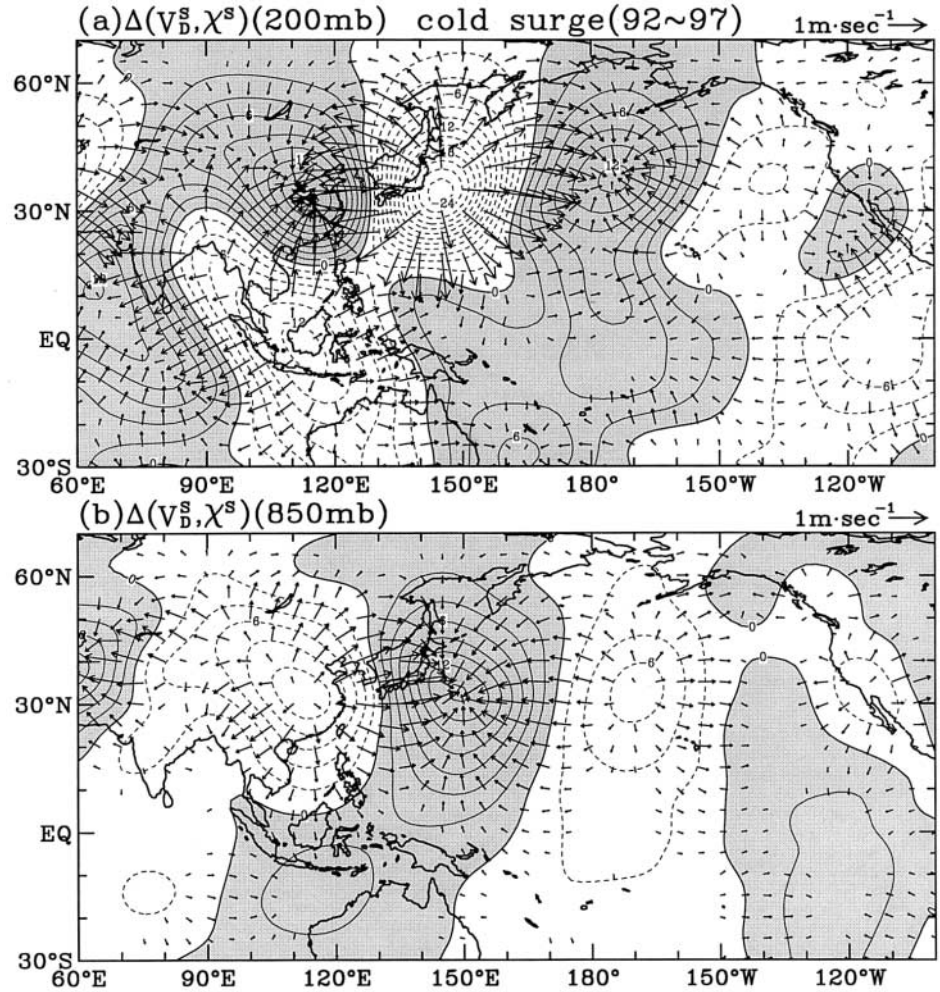

Fig. 6. Same as Fig. 5, except for the divergent circulation in the short-wave regime. The contour interval of $\Delta\chi^S$ is 2×10^5 m^{2}s^{-1}.

waves:

$$\Delta\psi^S = \Psi^S e^{i(kx+\ell y-\omega t)}, \tag{3a}$$

$$\Delta\chi^S = X^S e^{i(kx+\ell y-\omega t)}. \tag{3b}$$

As indicated by our diagnostic analysis (whose detail is not shown in Fig. 5), the streamfunction budget equation, Eq. (2), is a good approximation for the upper troposphere, but ψ^S_{A1} is negligible in the lower troposphere because zonal flow is weaker. For discussion, values of $\Delta\psi^S_{\chi 1} \geq 30$ m^{2}s^{-2} (heavily stippled) and $\Delta\psi^S_{\chi 1} \leq -30$ m^{2}s^{-2} (lightly stippled) are superimposed on the $\Delta\psi^S$ anomalies shown in Fig. 5. Substituting Eq. (3) into Eq. (2), one can obtain

$$\Delta\psi^S = \frac{C_I}{[u_Z - (c + c_R)]}\Delta\chi^S e^{-i\pi/2}$$

$$\text{for upper troposphere,} \tag{4a}$$

$$\Delta\psi^S = \frac{c_I}{(c + c_R)}\Delta\chi^S e^{-i\pi/2}$$

$$\text{for lower troposphere,} \tag{4b}$$

where $c_I = f/k$, $c = \omega/k$, and $c_R = \beta/(k^2 + \ell^2)$. u_Z and f are mean zonal flow and Coriolis parameter, respectively.

The spatially quadrature relationship between $\Delta\psi^S$ and $\Delta\chi^S$ is represented by the factor $e^{-i\pi/2}$ in Eq. (4). The question remaining is how the local Hadley circulation interacts with cold-surge disturbances. Expressing $\Delta\psi^S_{\chi 1}$ with $\Delta\chi^S$ in Eq. (3b) one may obtain

$$\Delta\psi^S_{\chi 1} = f(k^2 + \ell^2)\Delta\chi^S. \tag{5}$$

Substituting (5) into (4), we can easily find that $\Delta\psi^S$ and $\Delta\psi^S_{\chi 1}$ are spatially in quadrature as shown in Fig. 5. The negative $\Delta\psi^S_{\chi 1}$ (200 mb) cell in the upper troposphere, and the positive $\Delta\psi^S_{\chi 1}$ (850 mb) cell in the lower troposphere in East Asia, is actually associated with the downward branch of the local Hadley circulation. In other words, over this region, the local Hadley circulation provides a vorticity source to maintain the dipole of $\Delta\psi^S$ when the cold-surge disturbances propagate through this region. Evidently, the East-Asian local Hadley circulation is conducive to the establishment of a possible interaction between the tropical cumulus convection induced by cold surges, and the midlatitude cold-surge disturbances.

4. Concluding remarks

As reviewed by Lau and Li (1984) and Lau and Chang (1987), the tropical-midlatitude interaction in East Asia observed by previous studies may possibly be established by the intensified local Hadley circulation following cold surges. The Coriolis force induced by the upper southerly branch of this intensified circulation subsequently accelerates the East-Asian jet. However, this tropical-midlatitude interaction may be illustrated by a different perspective. The East Asian jet is located ahead of the east-coast trough. Thus, any mechanisms capable of perturbing the stationary waves in East Asia may result in the intensification of the East-Asian jet, and the activity of synoptic disturbances associated with this jet. Furthermore, as inferred from Fig. 2, the southward sweeping of the cold air mass following cold surges is possibly enhanced by the amplified Asian-continent ridge, and the deepening East-Asian trough. Consequently, the local Hadley circulation, and the tropical-midlatitude interaction, are intensified in East Asia. The alternative perspective of the cold-surge related tropical-midlatitude interaction motivates us to revisit three aspects of the East-Asian winter circulation system. Our findings are summarized as follows:

(1) Why is the East-Asian cold surge more effective in causing the tropical-midlatitude interaction?

Blocked by the upper-tropospheric Southeast-Asian high, the southward advection of East-Asian cold-air outbreaks underneath this high system forms the East-Southeast Asian cold surges. Consequently, a well-organized local Hadley circulation is developed by cold surges to facilitate the coupling between the East-Asian stationary waves and tropical convection.

(2) How is the East-Asian jet intensified accompanied with cold surges?

Propagating across the region between Northeast Asia and the Northwestern Pacific, cold-surge disturbances may amplify (deepen) the East-Asian stationary waves. In turn, the amplification of the East-Asian stationary waves, perturbed by cold-surge disturbances, results in the intensification of the East Asian jet.

(3) How does the intensified local Hadley cell by cold surges affect the midlatitude cold-surge disturbances?

As revealed from the streamfunction budget analysis, the enhancement of vortex compression by the downward branch of the intensified local Hadley circulation maintains the cold-surge induced dipole structure located in East Asia and its adjacent ocean.

The possible amplification of the East-Asian stationary waves by cold-surge disturbances may offer us a different perspective to explore the possible impact of the winter Asian monsoon on the regional climate change in tropical Southeast Asia and even North America. The winter monsoon vortices in tropical Southeast Asia, induced by cold surges, are major rain producers in this region (Cheang 1987). The amplification/weakening of the winter stationary waves in East Asia affects the cold surge activity. Thus, the interannual variation in the East-Asian cold surge activity related to that of midlatitude stationary waves and jet stream, may lead to the interannual variation in the tropical Southeast Asian monsoon rainfall. Our finding along this line will be reported by a future study. It is a well-established theory that the interannual variation of the North-American winter climate system is caused by the PNA teleconnection wave train, emanating from the tropical Pacific SST anomalies. Can the interannual variation in the tropical Southeast-Asian cumulus convection, enhanced by cold surges, induce a telelconnection wave train to affect the climate system on the downstream side over the Gulf of Alaska and North America? This possibility was substantiated by recent studies (Yang et al. 2002; Chen 2002).

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References

Blackmon, M.L., J.M. Wallace, N.C. Lau, and S.M. Mullen, 1977: An observational study of the Northern Hemisphere winter circulation. *J. Atmos. Sci.*, **84**, 1040–1053.

Chang, C.-P. and K.-M. Lau, 1980: Northerly cold surges and near-equatorial disturbances over the winter MONEX area during December 1974. Part II: Planetary-scale aspect. *Mon. Wea. Rev.*, **108**, 298–312.

——— and K.-G. Lum, 1985: Tropical-midlatitude interactions over Asia and the western Pacific Ocean during the 1983/84 northern winter. *Mon. Wea. Rev.*, **113**, 1345–1358.

Cheang, B.-K., 1987: Short- and long-range monsoon prediction in Southeast Asia. *Monsoons*, ed. by J.S. Fein and P.L. Stephens, John Wiley & Sons, (ISBN 0-471-87416-7), 579–606.

Chen, T.-C., 2002: A North-Pacific short-wave train during extreme phases of the ENSO cycle. *J. Climate*, **15**, 2359–2376.

———, R.-Y. Tzeng, and H. van Loon, 1988: A study on the maintenance of the winter subtropical jet streams in the northern hemisphere. *Tellus*, **40A**, 392–297.

———, M.-C. Yen, W.-R. Huang, and W. A. Gallus, 2002: An East-Asian Cold Surges: Case study. *Mon. Wea. Rev.*, **130**, 2271–2290.

Colle, B.A. and C.F. Mass, 1995: The structure and evolution of cold surges east of the Rocky Mountains. *Mon. Wea. Rev.*, **123**, 2577–2610.

Greenfield, R.S. and T.N. Krishnamurti, 1979: The Winter Monsoon Experiment—Report of December field phase. *Bull. Amer. Meteor. Soc.*, **60**, 439–444.

Horel, J.D. and J.M. Wallace, 1981: Planetary scale atmosphere and ocean. *Mon. Wea. Rev.*, **109**, 813–829.

James, I.J., 1994: *Introduction to Circulating Atmospheres.* Cambridge University Press (ISBN 0-521-41895X), 422 pp.

Joung, C.H. and M.H. Hitchman, 1982: On the role of successive downstream development in East Asian polar air outbreaks. *Mon. Wea. Rev.*, **110**, 122A–1237.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Krishnamurti, J.T., 1979: *Tropical Meteorology*. Compendium of Meteorology II. WMO, No. 364, ed. by Wiin-Nielsen. Geneva, World Meteorological Organization, 428 pp.

Lau, K.-M. and M.-T. Li, 1984: The monsoons of East Asia and its global associations—a survey. *Bull. Amer. Meteor. Soc.*, **65**, 114–125.

——— and C.P. Chang, 1987: Planetary scale aspects of the winter monsoon and atmospheric teleconnections. *Monsoon Meteorology*, ed. by C.P. Chang and T.N. Krishnamurti, Oxford University Press (ISBN 0-19-54254-9), 161–202.

———, ———, and P.H. Chan, 1983: Short-term planetary scale interaction over the tropics and midlatitude. II: Winter-MONEX period. *Mon. Wea. Rev.*, **111**, 1372–1385.

——— and co-authors, 2000: A report of the field operations and early results of the South China Sea Monsoon Experiment (SCSMEX). *Bull. Amer. Meteor. Soc.*, **81**, 1261–1270.

Lau, N.-C., 1979: The observed structure of tropospheric stationary waves in the local balances of vorticity and heat. *J. Atmos. Sci.*, **36**, 996–1016.

——— and K.-M. Lau, 1984: The structure and energetics of midlatitude disturbances accompanying cold air outbreak over East Asia. *Mon. Wea. Rev.*, **112**, 1309–1327.

——— and E.O. Holopainen, 1984: Transient eddy forcing of the time-mean flow as identified by geopotential tendencies. *J. Atmos. Sci.*, **41**, 313–328.

Namias, J. and P.F. Clapp, 1949: Confluence theory of the high tropospheric jet stream. *J. Meteor.*, **6**, 330–336.

Sanders, F., 1984: Quasi-geostrophic diagnosis of the monsoon depression of 5–9 July 1979. *J. Atmos. Sci.,* **41**, 538–552.

Schultz, D.M., W.E. Bracken, L.J. Bosart, G.F. Hakin, M.A. Bedrick, M.J. Dickinson, and K.R. Tyle, 1997: The 1993 superstorm cold surge: Frontal structure, gap flow, and tropical impact. *Mon. Wea. Rev.*, **125**, 5–38.

Wallace, J.M. and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.*, **109**, 784–812.

White, G.H., 1982: An observational study of the Northern Hemisphere extratropical summertime general circulation. *J. Atmos. Sci.,* **38**, 28–40.

Yang, S., K.-M. Lau, and K.-M. Kim, 2002: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.

Zhang, Y., K.R. Sperber, and J.S. Boyler, 1997: Climatology and interannual variation of the East Asian winter monsoon: Results from the 1979–95 NCEP/NCAR reanalysis. *Mon. Wea. Rev.*, **125**, 2605–2619.