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Intensification and Northward Extension of Northwest Pacific Anomalous Anticyclone in El Niño Decaying Mid-Summer: An Energetic Perspective

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Abstract

The Northwest Pacific (NWP) anomalous anticyclone (AAC) intensifies and extends northward from El Niño decaying early to mid-summer despite the dissipating sea surface temperature anomalies in the North Indian Ocean, North Atlantic and tropical NWP. The present study investigates these two intraseasonal variations of AAC from the perspective of energetics. The efficiency of dry energy conversion from background mean flow to perturbations in the El Niño decaying mid-summer is high and well explains the intensification of El Niño-induced circulation anomalies over the East Asia (EA)-NWP. The baroclinic energy conversion plays a more dominant role in this process than barotropic energy conversion. Besides, mean state changes over the EA-NWP from early to mid-summer are found in favor of the northward shift of the preferred latitude of the circulation anomalies. Thus, the El Niño-induced circulation anomalies over the EA-NWP are more northward-extended in the later period. Empirical orthogonal function analyses further confirm that the northward extension of El Niño-induced circulation anomalies over the EA-NWP stems from local optimal mode change from early to mid-summer.

Keywords El Niño; Anomalous Anticyclone; Intraseasonal variations; Energetics
Declarations

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Conflicts of interest
The authors declare no competing interests.

Availability of data and material
NCEP-DOE dataset is from https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html. The CPC Merged Analysis of Precipitation is from https://psl.noaa.gov/data/gridded/data.cmap.html. The OLR data is from https://psl.noaa.gov/data/gridded/data.interp_OLR.html. The SST dataset is from https://www.metoffice.gov.uk/hadobs/hadisst/.

Code availability
The code associated with this paper is available on request from K. H.

Authors' contributions
H.S., K.H. and G. H. conceived the study, performed the analyses, built the mechanism and wrote the paper.

Ethics approval
Not applicable

Consent to participate
Not applicable

Consent for publication
Not applicable
1. Introduction

Boreal summer is the principal rainy season for East Asia (EA) and Northwest Pacific (NWP). The precipitation here over this period shows immense interannual variability, which is of great socioeconomic importance for the livelihood of over two billion inhabitants (Wang et al. 2001; Huang et al. 2007). El Niño-Southern Oscillation (ENSO) is the leading source for local rainfall variability via giving rise to an anomalous anticyclone (AAC) in the lower troposphere over the Indo-NWP region during El Niño decaying summer (Fu and Ye 1988; Zhang et al. 1996; Wang et al. 2003; Wei et al. 2020). Similar with the Pacific–Japan (PJ) pattern (Nitta 1987) or the East Asia–Pacific (EAP) pattern (Huang and Wu 1989), the El Niño-induced convection anomalies over the NWP could excite a meridional wave train propagating into lower-level extratropical EA during El Niño decaying summer, bringing the influence of El Niño to the extratropics (Kosaka et al. 2013). For instance, the AAC can induce floods at its northern flank via moisture convergence (Huang and Wu 1989; Chang et al. 2000) and droughts in its ridge via subsidence motion (Wang et al. 2000). Besides, the AAC could lead to above-normal surface air temperature (SAT) anomalies in south China through reduced rainfall and downward vertical motion, while the anomalous cyclonic circulation to the north will bring about below-normal SAT anomalies in northeast China through upward vertical motion (Hu et al. 2011). Furthermore, the AAC could decrease tropical cyclones genesis over major parts of the tropical NWP (Du et al. 2011).

As for the maintenance mechanisms of the summer NWP AAC, El Niño-induced sea surface temperature (SST) anomalies in the tropical Indian Ocean, tropical Atlantic, and NWP are considered playing an important role. El Niño events generally mature in boreal winter with maximum SST warming in the equatorial eastern Pacific. In the following months, SST anomalies in the equatorial eastern Pacific decay rapidly, but the associated SST anomalies in the tropical Indian Ocean, tropical Atlantic, and NWP can maintain into summer via atmospheric bridge (Klein et al. 1999; Alexander et al. 2002), ocean dynamics (Xie et al. 2002; Huang and Kinter 2002) and air-sea interaction (Wang et al. 2000; Du et al. 2009; Kosaka et al. 2013; Xie et al. 2016). The warming in the tropical Indian Ocean and tropical Atlantic can
intensify the summer NWP AAC via the lower-level Ekman divergence invoked by warm
equatorial Kelvin wave response (Xie et al. 2009; Rong et al. 2010), while the NWP cooling
can intensify the AAC via the atmospheric descending Rossby wave response (Wang et al.
2000; Xiang et al. 2013).

The fundamental works of the last twenty years successfully explain the formation and
maintenance of AAC on the summer seasonal mean timescale, mainly focusing on the role of
SST anomalies in three tropical oceans. Nevertheless, the AAC is not only a mode tied to
anomalous SST forcing, but also could arise from the atmospheric internal dynamic processes
unrelated to SST variability (Kosaka et al. 2013; Zhou et al. 2018; Wang et al. 2018). Recent
studies illustrated that the AAC could extract kinetic energy ($KE$) from background mean flow
via barotropic energy conversion in the NWP confluence zone (Hu et al. 2019; Wang et al.
2020), implying that the impact of SST anomalies on the AAC becomes more efficient under
the summer NWP background mean state. However, the EA-NWP mean state changes
dramatically throughout the summer. So, how will the AAC change correspondingly?

Previous studies reveal an intensification (Xiang et al. 2013) and northward extension (Ye
and Lu 2010; Hu et al. 2017; Li and Lu 2018) of the AAC in El Niño decaying summer. As for
its mechanism, Ye and Lu (2010) suggested the northward shift of the upper-level westerly jet
and NWP subtropical high is responsible for the northward extension of the AAC, which is
confirmed by Kosaka and Nakamura (2010) where they conducted two numerical experiments
with the westerly jet axis set at 35°N and 50°N, respectively. They found the circulation
response is enhanced and displaced poleward in the later experiment. However, this induction
confuses people to some extent since the northward shift of the mid-latitude westerly jet is to
the disadvantage of Rossby wave propagation from the tropics to extratropics (Tsuyuki and
Kurihara 1989). Thus, the concrete process of changes in wave–mean flow interaction over the
EA-NWP during El Niño decaying summer entails further comprehension.

In this study, we aim to quantify the wave-mean flow interaction processes involved in
the intensification and northward extension of AAC during El Niño decaying summer from the
view of energetics. The remaining paper is structured as follows. Section 2 describes the data
and methods. Section 3 displays the variations of ocean-atmosphere anomalies in each month of El Niño decaying summer. The energy conversion between the AAC and background mean flow is diagnosed in section 4 to illustrate the influence of EA-NWP mean state changes on the AAC. Conclusions and discussion are given in section 5.

2. Data and methods

a. Datasets

In this study, the monthly and daily mean atmospheric variables are from the National Centers for the Environmental Prediction-Department of Energy (NCEP-DOE) atmospheric reanalysis, which has a horizontal resolution of 2.5°×2.5° at 17 height levels (Kanamitsu et al. 2002). Pentad-mean precipitation data is from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (Xie and Arkin 1997), given on a 2.5°×2.5° horizontal grid. The interpolated daily outgoing longwave radiation (OLR) data is from the National Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith 1996) and utilized as a proxy for convection, with 2.5°×2.5° horizontal resolution. The global gridded monthly SST dataset is from the UK. Met Office Hadley Centre, with 1°×1° horizontal resolution (Rayner et al. 2003). The study period is from January 1979 to December 2016.

b. Methods

This study focuses on the interannual variabilities associated with ENSO, so a 9-year running mean has been removed from all monthly and daily datasets to eliminate the decadal variability. The numeral 0 (1) in parentheses denotes the El Niño developing (decaying) years, and the months in this study all refer to those in the Northern Hemisphere. The Niño 3.4 index is defined as the December(0)-February(1) mean SST anomalies averaged over the region 5°S-5°N and 170°W-120°W and D(0)JF(1) is abbreviated as DJF(0). All the statistically significant tests for linear regression are performed using the two-tailed Student’s t test.

3. Variations of Ocean-Atmosphere anomalies in El Niño decaying summer

Figures 1 a, d, g show the regression of monthly 850 hPa wind and SAT anomalies in each month of El Niño decaying summer against the standardized DJF(0) Niño3.4 index. The AAC pattern persists throughout the summer, but its spatial structure and amplitude experience
pronounced changes in each month. The northern flank of AAC marches northward from 27°N in June(1) to 35°N in July(1) and 38°N in August(1). Besides, the intensity of AAC is observed to increase from June(1) to July(1) and August(1), corresponding with eastward extension of intensified zonally elongated circulation anomalies to the international date line. The AAC intensity is defined as the maximum regressed sea level pressure anomalies around the NWP (10°–20°N, 110°–150°E), and is 19, 123.174 and 94.727 Pa in June(1), July(1) and August(1), respectively.

Since the moisture is mainly confined in the lower troposphere, the pattern of regressed vertically integrated moisture fluxes highly resembles the AAC pattern in each month of El Niño decaying summer (Figs. 1b, e, h). Both SAT and rainfall anomalies display a meridional dipole pattern over the EA-NWP, with positive SAT and negative rainfall anomalies in the ridge of the AAC and opposite anomalies at its northern flank. Accompanied with the intensification and northward extension of AAC, the monthly SAT (Figs. 1 a, d, g) and rainfall (Figs. 1 b, e, h) anomalies over EA-NWP also gradually march northward. Specific in China, negative SAT and positive rainfall anomalies are observed around south China in June(1) and move to the mid-latitudes in July(1) and August(1), when the south China is occupied by positive SAT and negative rainfall anomalies. These results indicate that the El Niño-induced circulation and climate anomalies over the EA-NWP have pronounced intraseasonal and month-to-month variations during JJA(1) season.

Figures 1 c, f, i show the regression of SST anomalies in each month of El Niño decaying summer against standardized DJF(0) Niño3.4 index. In June(1), there is prominent warming in the tropical North Atlantic, tropical Indian Ocean, South China Sea, and cooling in the subtropical NWP. Such warm-warm-cold SST pattern from west to east is considered responsible for the formation and maintenance of the summer AAC (Xie et al. 2016; Jiang et al. 2017). However, the warming in the tropical North Atlantic, tropical Indian Ocean and cooling in the subtropical NWP are decaying in July(1) and August(1). The SST anomalies averaged over the North Atlantic (NA; 0°–20°N, 60°W–20°W), North Indian Ocean (NIO; 5°–25°N, 40°E–100°E) and NWP (10°–20°N, 150°–170°E) from June(1) to August(1) are
calculated. The values are 0.179 (0.216, -0.113), 0.133 (0.197, -0.034), 0.104 (0.171, -0.029) °C for NA (NIO, NWP) in June(1), July(1) and August(1), respectively. Obviously, the weakening warm-warm-cold SST pattern from June(1) to August(1) is not consistent with the intensification of the AAC.

To further illustrate the variations of AAC during post-El Niño summer, daily datasets are used to investigate the evolution feature of the AAC. Figure 2 shows the meridional section of pentad-mean precipitation, OLR, and 850 hPa wind anomalies averaged between 110° and 150°E regressed against the standardized DJF(0) Niño3.4 index. The northern flank of the AAC leaps from about 30°N in mid-June(1) to 35°N in late July(1), coinciding well with the anomalous rainband. The result indicates that the intraseasonal variations of the AAC does not accurately follow the calendar months, consistent with Hu et al. (2012). Thus, two periods are selected for further analysis. One is early summer(1) that is 15 June(1)-14 July(1), and the other is mid-summer(1) that is 20 July(1)-18 August(1), corresponding to the climatological EA and NWP rainy season, respectively. Since the weakening SST anomalies could not explain the AAC variations, what mechanism involved is responsible for its intensification and northward extension from early to mid-summer(1)?

4. Energetic analyses

To answer the above question, we first examine EA-NWP atmospheric mean state changes from early to mid-summer, then compare the efficiency of energy conversion from background mean flows to the AAC between the two periods.

a. Mean state changes from early to mid-summer

Figures 3a-b present the climatological 850 hPa winds and precipitation. The lower-level winds over the NWP feature a confluence between the westerly monsoon winds from the NIO and easterly trade winds associated with the North Pacific subtropical high. Accompanied with the advancement of the summer westerly monsoon, the confluence zone shifts eastward from early to mid-summer. As for precipitation, the mei-yu/baiu rainband withdraws, and the emergence of the NWP rainband centered approximately at 10°N, 135°E is observed from early to mid-summer. This convective jump (Ueda et al. 1995) is characterized by an abrupt
intensification of NWP convective activity in late July (Zhou et al. 2016) and may further exert influence on the change of the Rossby wave source over the NWP. Figures 3c-d show the climatological mean winds at 200 hPa and air temperature at 500 hPa. Accompanied with the northward shift of the solar radiation, high air temperature centers over the EA extend northward from early to mid-summer. The climatological upper-level westerly jet shifts northward from around 40°N in the early summer to around 45°N in the mid-summer according to the thermal wind relation (Lin and Lu 2008). The exit of the westerly jet over Japan weakens in the later period.

Previous studies suggest that zonally elongated cyclonic or anticyclonic circulation anomalies over the EA-NWP owe their formation to the configuration of local mean states (Kosaka and Nakamura 2006; 2010; Hirota and Takahashi 2012; Hu et al. 2019). There are five key energy conversion/generation processes at play. First, the lower-level climatological mean winds over the NWP feature a confluence between the westerly monsoon winds and easterly trade winds, which is conducive to zonally-elongated circulation anomalies gaining kinetic energy (KE) from the background mean flow. Second, since the inhomogeneity of the mean flow could energize the perturbations in the midlatitude (Simmons et al. 1983; Branstator 1985), zonally-elongated circulation anomalies tend to gain KE from the background mean flow in the exit of the climatological upper-level westerly jet. Third, circulation anomalies tilting westward with height are prone to gain available potential energy (APE) from the background mean flow in the upstream of westerly jet exit. Fourth, on the coastal areas of east Asia, the temperature gradient between warm continent and cold ocean is beneficial for circulation anomalies tilting northward with height to gain APE from the background mean flow. Fifth, active cumulus convection over the NWP could serve as an important energy source to provide APE for the perturbations. The above energy conversion/generation processes are vital to the formation of robust interannual variabilities over the EA-NWP, which are usually characterized by zonally-elongated horizontal pattern and northwestward tilting vertical structure, such as the PJ pattern (Xu et al. 2019; Zhu et al. 2020). As suggested in Figure 3, the NWP background mean states
change dramatically from early to mid-summer, then how will these changes lead to variations in El Niño-induced circulation anomalies over the EA-NWP?

b. Variations in El Niño-induced circulation anomalies from early to mid-summer(1)

Figures 4a-d show the regression of vorticity anomalies at 850 hPa and 200 hPa against standardized DJF(0) Niño3.4 index and corresponding wave-activity fluxes in the early and mid-summer. Following Takaya and Nakamura (2001), the wave-activity fluxes are defined as:

\[
W = \frac{1}{2|\bar{V}|} \begin{pmatrix}
\bar{u} (\psi_x'^2 - \psi_{xx}'^2) + \bar{v} (\psi_x' \psi_y' - \psi_{xy}'^2) \\
\bar{u} (\psi_x' \psi_y' - \psi_{xy}'^2) + \bar{v} (\psi_y'^2 - \psi_{yy}'^2) \\
f^2 / S \{ \bar{u} (\psi_x' \psi_p' - \psi_{xp}'^2) + \bar{v} (\psi_y' \psi_p' - \psi_{yp}'^2) \}
\end{pmatrix}
\]  

where \( \bar{V} \) is the horizontal wind velocity vector, \( \psi \) the stream function, \( f \) the Coriolis parameter, \( S = (R/p)(R\bar{T}/C_p p - d\bar{T}/dp) \) denotes the static stability, primes and overbars denote the regressed anomalies against standardized DJF(0) Niño3.4 index and climatological mean quantities, respectively. The direction of wave-activity fluxes denotes that of local group velocity of the stational Rossby wave.

In both early and mid-summer(1), the vorticity anomalies mainly feature meridional wave structure from the NWP to EA, corresponding to lower-tropospheric poleward wave fluxes. However, the wave fluxes between the two periods exhibit notable differences. The 850hPa wave fluxes in the mid-summer(1) are stronger and extend more northward than those in the early summer(1) (Figs. 4a-b). Notable upper-level equatorward wave fluxes can be seen over the subtropical NWP in the mid-summer(1), while they are missing in the early summer(1) (Figs. 4c-d). The result suggests that the stationary wave activities associated with the AAC pattern are remarkably different between the two periods. The tropical-extratropical coupling over the EA-NWP is more robust in the later period, which is attributed to the more prominent circulation anomalies at high latitudes of EA in the mid-summer(1). Since the AAC is the tropical lobe of El Niño-induced circulation anomalies over the EA-NWP, hereafter we focus on the El Niño-induced meridional circulation system rather than the single AAC at low latitudes.
Figures 4e-f show the latitude-height function of 135°E vorticity anomalies in the early and mid-summer regressed onto DJF(0) Niño3.4 index, respectively. In the early summer(1), the vorticity anomalies mainly feature a dipole structure, with phase tilting slight northward with height. The maximum negative and positive anomalies are distributed from 15°-25°N and 28°-33°N at lower troposphere, and are 20°-30°N and 30°-45°N at upper troposphere, highly resembling the PJ-related vorticity anomalies (Kosaka and Nakamura 2006). In the mid-summer(1), the vorticity anomalies at 135°E mainly feature a triple structure, with lower-tropospheric negative-positive-negative centers at 20°, 35° and 50°N, respectively, which shift northward by about 5° relative to that in the early summer(1). Apart from the shift of locations, the northward tilting of vorticity anomalies with height in the mid-summer(1) is stronger than those in the early summer(1), suggesting an intensified atmospheric baroclinicity in the later period. Besides, intensified upward wave fluxes appear at high latitudes of EA in the mid-summer(1), implying that the El Niño-induced circulation anomalies tend to extract APE from the background mean flow more efficiently in the mid-summer(1) than in the early summer(1). As a result, the three-dimensional meridional circulation system develops stronger and lasts longer in the later period.

Figures 4g-h show the longitude-height function of the regressed vorticity anomalies at 40° and 45°N where the westerly jet cores in the early and mid-summer(1) are located, respectively. Significant positive vorticity anomalies tilt slightly westward with height in the upstream of westerly jet exit while eastward in the downstream in both early and mid-summer(1). Besides, there are pronounced upward (downward) wave fluxes associated with the westward (eastward) inclination in the mid-summer(1), suggesting an intensified upward propagation of wave energy in this period. Since the energy conversion efficiency depends on the relative position between background mean flow and the El Niño-induced circulation anomalies, we further investigate the concrete energy conversion processes in the next part.

c. Mechanisms for the intensification of El Niño-induced circulation anomalies

Following Kosaka and Nakamura (2006), the barotropic energy conversion (CK) from the background mean flow to perturbations can be given by
\[ CK = \frac{v'^2 - u'^2}{2} \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) - u'v' \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \]  

(2)

where \( u \) and \( v \) denote the zonal and meridional winds, respectively. The baroclinic energy conversion (\( CP \)) from the background mean flow to perturbations is defined as

\[ CP = \frac{R f}{S_p} u' t' \frac{\partial \bar{v}}{\partial p} - \frac{R f}{S_p} v' t' \frac{\partial \bar{u}}{\partial p} \]  

(3)

where \( R \) denotes the gas constant, \( t \) the temperature, \( C_p \) the specific heat at constant pressure, and \( P \) the pressure. To objectively measure the efficiency of \( CK \) and \( CP \) in replenishing the El Niño-induced circulation anomalies over the EA-NWP, we calculate dry energy conversion time scale: \( \tau_{dry} = [KE + APE]/[CK + CP] \), where the bracket represents the area mean of 0–60°N, 110°–150°E. The qualitative result does not change too much even if the chosen area is slightly enlarged or shrank. Positive value less than 30 days indicates the corresponding process is efficient enough to maintain the El Niño-induced circulation anomalies over the EA-NWP, while value more than 30 days indicates the process is beneficial but not efficient. Negative value suggests that the process is detrimental to the maintenance of the El Niño-induced circulation anomalies. The \( \tau_{dry} \) is 7.241 and 3.804 days in early and mid-summer(1), respectively (Table 1), suggesting the El Niño-induced circulation anomalies over the EA-NWP can extract dry energy from the background mean flow more efficiently in the later period. As a result, the NWP AAC intensifies in this period. We further investigate the relative role played by \( CK \) and \( CP \) in the following paragraphs.

Figure 5 shows the \( CK \) at 850 hPa and 200 hPa during early and mid-summer(1). At 850 hPa, pronounced positive \( CK \) lies on the climatological zonal winds’ confluence zone \( (\partial u/\partial x < 0) \) from the South China Sea to the east of the Philippine in both periods (Figs. 5a-b). The fixed position of positive \( CK \) by the NWP convergent background mean flow could explain, at least in part, why the southern flank of AAC is anchored around 10°N in both early and mid-summer(1) (Fig. 2). Further analysis suggests that \( CK_x \) [especially -(\( u'^2 / 2 \))(\( \partial \bar{u} / \partial x \))] plays a dominant role in inducing lower-level \( CK \) due to the zonally elongated shape of AAC.
\((u'^2 + v'^2)\), emphasizing the importance of interaction between background zonal mean flow and circulation anomalies in triggering the AAC (figure not shown).

At 200 hPa, the positive and negative \(CK\) adjoin one another around the exit of the upper-level westerly jet \((\partial u/\partial x < 0)\). The westerly jet advances northward and weakens from early to mid-summer(1) and so does the \(CK\) along the westerly jet (Figs. 5c-d). Another conspicuous positive \(CK\) center is found in the Okhotsk sea in the mid-summer(1) (Fig. 5d). Since the direction of the wave fluxes and momentum fluxes is opposite with each other, the salient equatorward wave fluxes over the Okhotsk sea (Fig. 4d) denote strong poleward momentum fluxes \((u'/v' > 0)\). Thus, these poleward momentum fluxes to the north of the westerly jet core \((\partial u/\partial y < 0)\) favor the formation of positive \(CK\) \([−u'v'(\partial u/\partial y) > 0]\).

The barotropic energy conversion time scale is defined as \(\tau_{CK} = [KE]/[CK]\). The \(\tau_{CK}\) is 9.538 and 15.574 days at 850 hPa, 2.756 and 7.729 days at 200 hPa, and 5.563 and 7.58 days when integrated vertically in the early and mid-summer(1), respectively (Table 1). The result indicates that \(CK\) is efficient in both early and mid-summer(1), but more efficient in the former period. That is to say, the El Niño-induced circulation anomalies over the EA-NWP can more efficiently gain barotropic energy from the background mean flow in the early summer(1) than in the mid-summer(1). Thus, \(CK\) plays a negative role in the intensification of El Niño-induced circulation anomalies over the EA-NWP. On the other hand, it should be noted that Eq. (1) dismisses the redistribution of \(KE\) from one area to the other, so the simple area average may import errors. However, this method is still a good way to preliminarily quantify the wave-mean flow interaction.

Figure 6 shows the vertically integrated \(CP\) and climatological mean temperature at 500 hPa during early and mid-summer(1). The most pronounced positive \(CP\) over the EA in the early summer(1) is situated from Korean Peninsula to the Japan Sea. The positive \(CP\) remarkably intensifies and advances northward to the Far East in the mid-summer(1), with its shape changing from the zonally-elongated to northeastward-slanted. We further decompose \(CP\) into \(CP_x\) and \(CP_y\) (Figs. 6c-f). \(CP_x\) makes marginal contributions in the early summer(1) but comes into play in the mid-summer(1). The positive \(CP_x\) over the Okhotsk sea in the later
period facilitates the positive \( CP \), resulting from an intensified interaction between eastward heat transport \((u't' > 0)\) and thermal contrast between the warm continent and cold ocean \((\partial \bar{v}/\partial p > 0)\). Positive \( CP_y \) is of paramount importance in positive \( CP \). Since the direction of the vertical wave fluxes and heat fluxes is the same, the salient upward wave fluxes denote strong poleward heat fluxes \((v't' > 0)\). Due to the existence of meridional temperature gradient, \( \partial u/\partial p < 0 \) exists in mid-latitudes of EA. Thus, the structure of westward tilt with height \((-v't' < 0)\) is to the benefit of positive \( CP_y \) \((-v't'(\partial \bar{u}/\partial p) > 0)\). The baroclinicity of the atmosphere is pronounced at mid-high latitudes of EA, leading to stronger \( CP \) in the mid-summer(1). As a result, the El Niño-induced circulation anomalies over the EA-NWP in the later period are robust.

The efficiency of \( CP \) in replenishing the local \( APE \) of perturbations is measured by \( \tau_{CP} = [APE]/[CP] \). The \( \tau_{CP} \) is 11.689 and 1.618 days in early and mid-summer(1), respectively (Table 1), indicating that \( CP \) can energize the El Niño-induced circulation anomalies much more effectively in the later period. Thus, \( CP \) may account for why the El Niño-induced circulation anomalies intensify when the anomalous SST forcing weakens in the mid-summer(1).

d. Mechanisms for the northward extension of El Niño-induced circulation anomalies

In the last section, we investigate the mechanisms for intensification of El Niño-induced circulation anomalies over the EA-NWP in mid-summer(1) via comparison of energy conversion efficiency in two periods. In this part, we further discuss the mechanisms for the northward extension of El Niño-induced circulation anomalies over the EA-NWP. Kosaka and Nakamura (2010) demonstrated that the mode which can extract energy from background mean states most efficiently is the one most sustainable. Thus, every mode has a preferred latitude or longitude phase. Here, we analyze whether the El Niño-induced circulation anomalies over the EA-NWP during the early and mid-summer(1) are the modes which can maximize the efficiency of energy conversion.

Following Kosaka and Nakamura (2010), we artificially displace the El Niño-induced circulation anomalies over the EA-NWP by every 5° in latitude, while the climatological
background mean states are fixed. Through moving the modes meridionally, we aim to examine whether these modes are the dynamic modes inherent in the background mean states.

Table 2 gives the time scales with which the El Niño-induced circulation anomalies could gain energy after the anomalous circulation pattern is shifted meridionally relative to its original location. The result shows that the El Niño-induced circulation anomalies over the EA-NWP gain dry energy from background mean flow most efficiently at the original latitude in both two periods. The El Niño-induced circulation anomalies in the early and mid-summer(1) both are the optimal modes, and their locations are fixed meridionally according to the background mean flow. Background mean flow shifts northward from the early to mid-summer(1) and leads to resultant northward extension of anomalous meridional circulation system.

On the other hand, it should be noted that the artificially displaced circulation anomalies no longer meet the thermal or vorticity balance, so we verify the results by additional empirical orthogonal function (EOF) analyses. We perform EOF analyses on the 850 hPa vorticity anomalies over the EA-NWP (10°-60°N, 100°–160°E) from 1979 to 2016 in the early and mid-summer, respectively (Figs. 7a, b). The domain of EOF analysis is same as that in Kubota et al. (2016). The leading EOF modes in the early and mid-summer explain 18.094% and 20.21%, respectively, both are well separated with other modes by the criterion of North et al. (1982). The EOF1 modes feature an AAC pattern over the NWP in early and mid-summer, while extending more northward in the later period. Since the EOF1 normally captures the dominant mode of the interannual variability, the result suggests that the circulation anomalies over the EA-NWP tend to occur in a more northward position in the mid-summer. PC1s in the early and mid-summer are highly correlated with DJF(0) Niño3.4 index (r = 0.46 and 0.466, respectively, both p < 0.01, n = 38).

We further use partial correlation method to remove the influence of ENSO, and perform EOF analyses again on the residues in the early and mid-summer(1), respectively (Figs. 7c, d). Thus, we get the dominant mode of atmospheric interannual variability over the EA-NWP independent of ENSO. The patterns are almost the same as those presented in Figs. 7a, b, and the correlations between PC1s in the early and mid-summer and DJF(0) Niño3.4 index are
both nearly zero this time. The result further confirms that the northward extension of El Niño-induced circulation anomalies over the EA-NWP stems from local optimal internal mode change from early to mid-summer, which is independent of ENSO.

5. Conclusions and discussion

a. Conclusions

We have investigated the intraseasonal variations of the AAC during El Niño decaying summer and explained these phenomena from the perspective of energetics. It is noted that the El Niño-induced circulation anomalies over the EA-NWP are stronger and more northward-extended in July(1) and August(1) than in June(1), while the decaying SST anomalies over the NIO, NA and NWP could not account for this shift (Fig. 1). Based on daily datasets, we further divide the study period into early summer(1) [15 June(1)-14 July(1)] and mid-summer(1) [20 July(1)-18 August(1)], which is more accurate than month division since the most pronounced AAC transition occurs in late July(1) (Fig. 2).

Then we diagnose the El Niño-induced circulation anomalies over the EA-NWP from the perspective of energetics and draw the following three conclusions. First, El Niño will induce more prominent circulation anomalies at high latitudes of EA in the mid-summer(1) than in the early summer(1), associated with more salient lower-level poleward wave fluxes originating from the NWP and injecting upward in the upstream of westerly jet exit in the later period (Fig. 4). It suggests the tropical-extratropical coupling over the EA-NWP is more robust in the mid-summer(1) from the view of atmospheric wave. Second, dry energy conversion from the background mean flow to perturbations over the NWP-EA is more efficient in the El Niño decaying mid-summer than in the early summer, well explaining the intensification of El Niño-induced circulation anomalies (Table 1). CP (especially $C_P$) plays a more dominant role in this process than CK (Figs. 5,6). Third, through artificially displacing the El Niño-induced circulation anomalies over the EA-NWP in the meridional direction, it is found that only at the original latitude can the El Niño-induced circulation anomalies gain dry energy from the background mean flow most efficiently (Table 2), suggesting the original latitude is the preferred latitude of the El Niño-induced circulation anomalies. Mean state changes over the
EA-NWP from early to mid-summer favor the northward shift of the preferred latitude of the circulation anomalies. Thus, the El Niño-induced circulation anomalies over the EA-NWP are more northward-extended in the later period. Additional EOF analyses further confirm that the northward extension of El Niño-induced circulation anomalies over the EA-NWP stems from local optimal internal mode change from early to mid-summer, which is independent of ENSO (Fig. 7).

b. Discussion

In this study, we calculate $CK$ and $CP$ to explain the intensification of the AAC. On the other hand, we use perturbation displacement method and EOF to discover the optimal internal mode over the EA-NWP and further explain the northward extension of the AAC. In fact, the above two points of view are not independent but complementary to each other. The northward shift of $CK$ and $CP$ in the mid-summer (1) (Figs. 5,6) can also explain the northward extension of the AAC while the enhanced optimal internal mode in the mid-summer (Figs. 7a,b) can also elucidate the intensification of the AAC. Since every method has its limitation, this cross-validation thought is frequently used in the energetics to increase the reliability of the conclusion (Kosaka and Nakamura 2010).

Besides, although the results shown in this study are confined to NWP AAC during El Niño decaying summer, local optimal mode change due to mean state changes in the mid-summer may render all intraseasonal to monthly perturbations over the EA-NWP stronger and more northward-extended, expanding the implications of this study. It can also be inferred that the extratropical circulation of EA is of a higher predictability in the mid-summer since the tropical-extratropical coupling is stronger in this period. The pioneering work of Tsuyuki and Kurihara (1989) suggested that the intraseasonal PJ pattern is inclined to be more energetic in the mid-summer than in the early summer, which also supports the conjecture.

Furthermore, it should be noted that the vertical shear of background zonal mean flow is important for the transformation from the baroclinic structure into a barotropic structure to convey the thermally induced baroclinic disturbances to the extratropics (e.g., Wang and Xie 1996). As suggested by Lu (2004), the easterly shear of background zonal mean flow over the
NWP is robust in August while nearly neutral in June, thus the El Niño-induced local convection anomalies could induce stronger circulation anomalies in mid-high latitudes of EA in the mid-summer (Figs. 4a-d).

Last but not the least, it’s worth noting that the moist process is also of great significance to amplify the AAC (Kosaka and Nakamura 2006; Hu et al. 2019), while the present study dismisses detailed analysis of this process. Since the climatological mean precipitation over the NWP enhances from early to mid-summer (Figs. 3a-b; Xiang et al. 2013), the local atmospheric response becomes more sensitive to external forcing (Wu et al. 2010), thus an intensified AAC will ensue. Since the AAC is interactively correlated with the anomalous negative precipitation in its ridge (Xie et al. 2009) and anomalous rainband at its northern flank (Lu and Lin 2009; Matsumura et al. 2015), it is difficult to truly separate circulation from convection and investigate the causality between each other, which deserves future studies.
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References

Alexander MA, Bladé I, Newman M, Lanzante JR, Lau NC, Scott JD (2002) 2002: The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. J Climate 15 (16):2205-2231

Branstator G (1985) Analysis of General Circulation Model Sea-Surface Temperature Anomaly Simulations Using a Linear Model. Part I: Forced Solutions. J Atmos Sci 42 (21):2225–2241

Chang CP, Zhang Y, Li T (2000) Interannual and Interdecadal Variations of the East Asian Summer Monsoon and Tropical Pacific SSTs. Part I: Roles of the Subtropical Ridge. J Clim 13 (24):4310-4325

Du Y, Xie S-P, Huang G, Hu K (2009) Role of Air–Sea Interaction in the Long Persistence of El Niño–Induced North Indian Ocean Warming. J Clim 22 (8):2023-2038

Du Y, Yang L, Xie SP (2011) Tropical Indian Ocean Influence on Northwest Pacific Tropical Cyclones in Summer Following Strong El NinoEl Niño. J Clim 24 (1):315-322

Fu C, Ye D (1988) The Tropical Very Low-Frequency Oscillation on Interannual Scale. Adv Atmos Sci 5 (3):369–388

Hirota N, Takahashi M (2012) A tripolar pattern as an internal mode of the East Asian summer monsoon. Clim Dyn 39:2219–2238

Hu K, Huang G, Huang R (2011) The Impact of Tropical Indian Ocean Variability on Summer Surface Air Temperature in China. J Clim 24 (20):5365-5377

Hu K, Huang G, Qu X, Huang R (2012) The impact of Indian Ocean variability on high temperature extremes across the southern Yangtze River valley in late summer. Adv Atmos Sci 29 (1):91-100

Hu K, Huang G, Xie S-P, Long S-M (2019) Effect of the mean flow on the anomalous anticyclone over the Indo-Northwest Pacific in post-El Niño summers. Clim Dyn 53 (9-10):5725-5741

Hu K, Xie S-P, Huang G (2017) Orographically Anchored El Niño Effect on Summer Rainfall in Central China. J Clim 30 (24):10037-10045
Huang B, Kinter JL III (2002) Interannual variability in the tropical Indian Ocean. J Geophys Res 107(C11):3199

Huang R, Chen J, Huang G (2007) Characteristics and Variations of the East Asian Monsoon System and Its Impacts on Climate Disasters in China. Adv Atmos Sci 24:993–1023

Huang R, Wu Y (1989) The Influence of ENSO on the Summer Climate Change in China and Its Mechanism. Adv Atmos Sci 6 (1):21-32

Jiang W, Huang G, Hu K, Wu R, Gong H, Chen X, Tao W (2017) Diverse Relationship between ENSO and the Northwest Pacific Summer Climate among CMIP5 Models: Dependence on the ENSO Decay Pace. J Clim 30 (1):109-127

Kanamitsu M, Ebisuzaki W, Woollen J, Yang SK, Hnilo JJ, Fiorino M, Potter GL (2002) NCEP–DOE AMIP-II Reanalysis (R-2). Bull Am Meteorol Soc 83 (11):1631-1643

Klein SA, Soden BJ, Lau NC (1999) Remote Sea Surface Temperature Variations during ENSO: Evidence for a Tropical Atmospheric Bridge. J Clim 12 (4):917-932

Kosaka Y, Nakamura H (2006) Structure and dynamics of the summertime Pacific–Japan teleconnection pattern. Q J R Meteorol Soc 132 (619):2009-2030

Kosaka Y, Nakamura H (2010) Mechanisms of Meridional Teleconnection Observed between a Summer Monsoon System and a Subtropical Anticyclone. Part I: The Pacific–Japan Pattern. J Clim 23 (19):5085-5108

Kosaka Y, Xie SP, Lau NC, Vecchi GA (2013) Origin of seasonal predictability for summer climate over the Northwestern Pacific. Proc Natl Acad Sci 110 (19):7574-7579

Kubota H, Kosaka Y, Xie S-P (2016) A 117-year long index of the Pacific-Japan pattern with application to interdecadal variability. Int J Climatol 36 (4):1575–1589

Li X, Lu R (2018) Subseasonal Change in the Seesaw Pattern of Precipitation between the Yangtze River Basin and the Tropical Western North Pacific during Summer. Adv Atmos Sci 35 (10):1231–1242

Liebmann B, Smith CA (1996) Description of a Complete (Interpolated) Outgoing Longwave Radiation Dataset. Bull Am Meteorol Soc 77:1275-1277
Lin Z, Lu R (2008) Abrupt Northward Jump of the East Asian Upper-Tropospheric Jet Stream in Mid-Summer. J Meteorol Soci Jpn 86 (6):857-866

Lu R (2004) Associations among the Components of the East Asian Summer Monsoon System in the Meridional Direction. J Meteorol Soci Jpn 82 (1):155-165

Lu R, Lin Z (2009) Role of Subtropical Precipitation Anomalies in Maintaining the Summertime Meridional Teleconnection over the Western North Pacific and East Asia. J Clim 22 (8):2058-2072

Matsumura S, Sugimoto S, Sato T (2015) Recent Intensification of the Western Pacific Subtropical High Associated with the East Asian Summer Monsoon. J Clim 28 (7):2873-2883

Nitta T (1987) Convective activities in the tropical western Pacific and their impact on the northern hemisphere summer circulation. J Meteorol Soci Jpn 65:165–171

North GR, Bell TL, Cahalan RF, Moeng FJ (1982) Sampling errors in the estimation of empirical orthogonal functions. Mon Weather Rev 110 (7):699–706

Rayner N, Parker D, Horton E, Folland C, Alexander L, Rowell D, Kent E, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res Atmos 108 (D14):4407

Rong X, Zhang R, Li T (2010) Impacts of Atlantic sea surface temperature anomalies on Indo-East Asian summer monsoon-ENSO relationship. Chin Sci Bull 55 (22):2458–2468

Simmons A, Wallace J, Branstator G (1983) Barotropic wave propagation and instability, and atmospheric teleconnection patterns. J Atmos Sci 40:1363–1392

Takaya K, Nakamura H (2001) A Formulation of a Phase-Independent Wave-Activity Flux for Stationary and Migratory Quasigeostrophic Eddies on a Zonally Varying Basic Flow. J Atmos Sci 58 (6):608-627

Tsuyuki T, Kurihara K (1989) Impact of Convective Activity in the Western Tropical Pacific on the East Asian Summer Circulation. J Meteorol Soci Jpn 67 (2):231-247
Ueda H, Yasunari T, Kawamura R (1995) Abrupt Seasonal Change of Large-Scale Convective Activity over the Western Pacific in the Northern Summer. J Meteorol Soc Jpn 73 (4):795-809

Wang B, Xie X (1996) Low-Frequency Equatorial Waves in Vertically Sheared Zonal Flow. Part I: Stable Waves. J Atmos Sci 53 (23):449-467

Wang B, Wu R, Fu X (2000) Pacific-East Asian Teleconnection: How Does ENSO Affect East Asian Climate? J Clim 13 (9):1517-1536

Wang B, Wu R, Lau KM (2001) Interannual Variability of the Asian Summer Monsoon: Contrasts between the Indian and the Western North Pacific–East Asian Monsoons. J Clim 14 (20):4073-4090

Wang B, Wu R, Li T (2003) Atmosphere–Warm Ocean Interaction and Its Impacts on Asian–Australian Monsoon Variation. J Clim 16 (8):1195-1211

Wang C-Y, Xie S-P, Kosaka Y (2018) Indo-Western Pacific Climate Variability: ENSO Forcing and Internal Dynamics in a Tropical Pacific Pacemaker Simulation. J Clim 31 (24):10123–10139

Wang X, Xie SP, Guan Z (2020) Atmospheric Internal Variability in the Summer Indo–Northwestern Pacific: Role of the Intraseasonal Oscillation. J Clim 33 (8):3395–3410

Wei, K., C. Ouyang, H. Duan, Y. Li, M. Chen, J. Ma, H. An and S. Zhou (2020) Reflections on the catastrophic 2020 yangtze river basin flooding in southern china. The Innovation 2(1):100038

Wu B, Li T, Zhou T (2010) Relative Contributions of the Indian Ocean and Local SST Anomalies to the Maintenance of the Western North Pacific Anomalous Anticyclone during the El Niño Decaying Summer. J Clim 23 (11):2974-2986

Xiang B, Wang B, Yu W, Xu S (2013) How can anomalous western North Pacific Subtropical High intensify in late summer? Geophys Res Lett 40 (10):2349-2354

Xie P, Arkin PA (1997) Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates. Bull Am Meteorol Soc 78 (11):2539-2558
Xie S-P, Hu K, Hafner J, Tokinaga H, Du Y, Huang G, Sampe T (2009) Indian Ocean Capacitor Effect on Indo–Western Pacific Climate during the Summer following El Niño. J Clim 22 (3):730-747

Xie S-P, Kosaka Y, Du Y, Hu K, Chowdary JS, Huang G (2016) Indo-western Pacific ocean capacitor and coherent climate anomalies in post-ENSO summer: A review. Adv Atmos Sci 33 (4):411-432

Xie SP, Annamalai H, Schott FA, Mccreary JP (2002) Structure and Mechanisms of South Indian Ocean Climate Variability. J Clim 15 (8):864–878

Xu P, Wang L, Chen W, Feng J, Liu Y (2019) Structural Changes in the Pacific–Japan Pattern in the Late 1990s. J Clim 32 (2):607-621

Ye H, Lu R (2010) Subseasonal Variation in ENSO-Related East Asian Rainfall Anomalies during Summer and Its Role in Weakening the Relationship between the ENSO and Summer Rainfall in Eastern China since the Late 1970s. J Clim 24 (9):2271-2284

Zhang R, Sumi A, Kimoto M (1996) Impact of El Niño on the East Asian monsoon : A diagnostic study of the '86/87 and '91/92 events. J Meteorol Soci Jpn 74 (1):49-62

Zhou W, Xie S-P, Zhou Z-Q (2016) Slow Preconditioning for the Abrupt Convective Jump over the Northwest Pacific during Summer. J Clim 29 (22):8103-8113

Zhou Z-Q, Xie S-P, Zhang G, Zhou W (2018) Evaluating AMIP Skill in Simulating Interannual Variability over the Indo-Western Pacific. J Clim 31 (6):2253–2265

Zhu Y, Wen Z, Guo Y, Chen R, Li X, Qiao Y (2020) The characteristics and possible growth mechanisms of the quasi-biweekly Pacific–Japan teleconnection in Boreal Summer. Clim Dyn 55:3363–3380
Figure Captions:

Figure 1. (Left) 850 hPa wind (vectors) and SAT (colors) anomalies, (middle) vertically integrated (from the surface to 200 hPa) moisture fluxes (vectors) and their divergence (colors), (right) SST anomalies (colors) in (a, b, c) June, (d, e, f) July, (g, h, i) August regressed against standardized DJF(0) Niño3.4 index for 1978/79–2015/16. Vectors only exceeding the 90% confidence level are shown and dots indicate that the anomalies are significant at the 90% confidence level. The hatched areas from west to east (c) indicate NA, NIO and NWP, respectively.

Figure 2. 850 hPa wind (vectors, shown only exceeding the 90% confidence level), precipitation (colors, dots indicate that the anomalies are significant at the 90% confidence level) and OLR (contours for ±2, ±4, ±6, ±8) anomalies averaged between 110°-150°E regressed against standardized DJF(0) Niño3.4 index for 1978/79–2015/16. Solid and dashed contours represent negative and positive convection anomalies, respectively. Early summer(1) is defined as 15 June(1)–14 July(1) and mid-summer(1) 20 July(1)–18 August(1).

Figure 3. Climatological mean horizontal winds (vectors) at 850 hPa (a, b) and 200 hPa (c, d), superimposed on the climatological mean precipitation (colors; a, b) and air temperature at 500 hPa (colors; c, d) in the early and mid-summer. Climatological mean zonal winds are also overlaid (contours for 15, 20, 25, 30 m/s; c, d).

Figure 4. Relative vorticity anomalies (colors, dots indicate that the anomalies are significant at the 90% confidence level) at (a, b) 850 hPa and (c, d) 200 hPa in (a, c) early summer, (b, d) mid-summer regressed against standardized DJF(0) Niño3.4 index for 1978/79–2015/16. Meridional section of regressed vorticity anomalies (colors) at (e, f) 135°E in the early and mid-summer(1), respectively. Zonal section of regressed vorticity anomalies (colors) at (g) 40° and (h) 45°N in the early and mid-summer(1), respectively. Vectors denote the corresponding wave fluxes.

Figure 5. Barotropic energy conversion $CK$ at 850 hPa and 200 hPa during El Niño decaying early summer (a, c) and mid-summer (b, d).
Figure 6. Vertically integrated (1000-200 hPa) baroclinic energy conversion $CP$ (colors) and climatological mean temperature at 500 hPa (contours, °C) during El Niño decaying early summer (a) and mid-summer (b). Also shown are $CP_x$ and $CP_y$ in the Eq. (2) during El Niño decaying early summer (c, e) and mid-summer (d, f).

Figure 7. 850 hPa wind anomalies (vectors) regressed against standardized PC1 of the EOF analyses performed on standardized 850 hPa vorticity anomalies over the EA-NWP (10°-60°N, 100°–160°E) during El Niño decaying early summer (a) and mid-summer (b). c (d) is the same as a (b) but on the 850 hPa vorticity anomalies independent of ENSO. Vectors only exceeding the 90% confidence level are shown.
Table 1. Time scales (days) with which the El Niño-induced circulation anomalies could gain energy from barotropic energy conversion ($\mathcal{C}_K$), baroclinic energy conversion ($\mathcal{C}_P$) and dry energy conversion ($\mathcal{C}_K + \mathcal{C}_P$) during El Niño decaying early summer and mid-summer. The eddy energy and energy conversions are integrated vertically from 1000 to 200 hPa and then horizontally over 0-60°N, 110°-150°E.

|                | 0-60°N, 110°-150°E | Early summer(1) | Mid-summer(1) |
|----------------|-------------------|-----------------|---------------|
| $\tau_{\mathcal{C}_K}$ 850 hPa | 9.538             | 15.574          |
| $\tau_{\mathcal{C}_K}$ 200 hPa | 2.756             | 7.729           |
| $\tau_{\mathcal{C}_K}$ Vertical integral | 5.659             | 7.636           |
| $\tau_{\mathcal{C}_P}$ Vertical integral | 11.253           | 1.597           |
| $\tau_{\text{dry}}$ Vertical integral | 7.15             | 3.797           |

Table 2. Time scales (days) with which the El Niño-induced circulation anomalies could gain energy after the circulation pattern is shifted meridionally relative to its original location. The eddy energy is calculated from the original circulation pattern and integrated over 0-60°N, 100°-160°E, whereas the energy conversions are integrated over the new domain shifted with the circulation pattern. Both the eddy energy and energy conversions are integrated vertically from 1000 to 200 hPa before integrated horizontally. The efficiencies in the original latitude are highlighted in shadow.

|                | $\tau_{\mathcal{C}_K}$ Early summer(1) | Mid-summer(1) | $\tau_{\mathcal{C}_P}$ Early summer(1) | Mid-summer(1) | $\tau_{\text{dry}}$ Early summer(1) | Mid-summer(1) |
|----------------|----------------------------------------|--------------|----------------------------------------|--------------|--------------------------------------|--------------|
| 15° northward | -7.976                                 | -45.036      | -10.07                                 | 2.068        | -8.738                               | 8.851        |
| 10° northward | -9.898                                 | 217.056      | -11.12                                 | 1.908        | -10.376                              | 6.969        |
| 5° northward  | 29.903                                 | 12.993       | 36.744                                 | 1.766        | 32.436                               | 4.814        |
| Original      | 5.659                                  | 7.636        | 11.253                                 | 1.597        | 7.15                                 | 3.797        |
| 5° southward  | 6.24                                   | 9.331        | -43.246                                | 1.595        | 11.996                               | 4.063        |
| 10° southward | 19.872                                 | 141.978      | -3.995                                 | 1.826        | -13.203                              | 6.597        |
| 15° southward | -5352.58                               | -10.994      | -2.322                                 | 2.506        | -5.533                               | 24.979       |
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Figures

Figure 1

(Left) 850 hPa wind (vectors) and SAT (colors) anomalies, (middle) vertically integrated (from the surface to 200 hPa) moisture fluxes (vectors) and their divergence (colors), (right) SST anomalies (colors) in (a, b, c) June, (d, e, f) July, (g, h, i) August regressed against standardized DJF(0) Niño3.4 index for 1978/79–2015/16. Vectors only exceeding the 90% confidence level are shown and dots indicate that the anomalies are significant at the 90% confidence level. The hatched areas from west to east (c) indicate NA, NIO and NWP, respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
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Figure 5

Barotropic energy conversion CK at 850 hPa and 200 hPa during El Niño decaying early summer (a, c) and mid-summer (b, d). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Vertically integrated (1000-200 hPa) baroclinic energy 629 conversion CP (colors) and climatological mean temperature at 500 hPa (contours, °C) during El Niño decaying early summer (a) and mid-summer (b). Also shown are $\cdots$ and $\cdots$ in the Eq. (2) during El Niño decaying early summer (c, e) and mid-summer (d, f). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any
Figure 7

850 hPa wind anomalies (vectors) regressed against standardized PC1 of the EOF analyses performed on standardized 850 hPa vorticity anomalies over the EA-NWP (10°-60°N, 100°–160°E) during El Niño decaying early summer (a) and mid-summer (b). c (d) is the same as a (b) but on the 850 hPa vorticity anomalies independent of ENSO. Vectors only exceeding the 90% confidence level are shown. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.