The Evolution Dynamical Processes of Ural Blocking Through the Lens of Local Finite-Amplitude Wave Activity Budget Analysis

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Abstract Understanding the dynamical processes of Ural blocking (UB) during its different phases of development is of great importance for the prediction of UB and the subsequent meteorological impacts in Asia. Using the 6-hourly ERA-Interim reanalysis data, this study quantifies the conservative and non-conservative processes in the lifecycle of UB through the lens of the hybrid Eulerian-Lagrangian local finite-amplitude wave activity (LWA) diagnostics. It is found that (a) as a wave activity source, eddy heat flux assists the zonal LWA flux in initiating the UB, it also works to prevent the wave activity of the blocking from dispersing downstream—the key characteristic of blocking; (b) both wave propagation and wave advection are indispensable for the evolution of UB, playing a tug-of-war on the downstream development of wave activity; (c) throughout the lifespan of UB, diabatic heating acts as a damping mechanism for the wave activity both upstream and downstream.

Plain Language Summary Midlatitude blocking is a distinct circulation phenomenon with unique stagnation in space and long persistence in time, and it is often considered to be originating from barotropic dynamics. Here a state-of-the-art analysis tool for diagnosing wave activity is applied to the blocks over Urals, aka UB, to provide a comprehensive evaluation of both barotropic and baroclinic, and both conservative and non-conservative processes during the formation, maintenance, and decay of UB. The result reveals distinct roles of these processes between the upwind and downwind sides of Urals, particularly underlining the importance of the baroclinic wave growth in the initiation phase of UB and in blocking the downstream development of the associated wave activity. An important corollary is that the conventional barotropic thinking may be inadequate for UB in the real atmosphere.

1. Introduction

Ural blocking (UB) occurs in the vicinity of the Ural Mountains (around 60°E), where the third frequency peak of the Northern Hemisphere blocking distribution is located (Diao et al., 2006; Dole & Gordon, 1983; Pelly & Hoskins, 2003; Tibaldi & Molteni, 1990). It often lasts longer than the typical synoptic time scale, likely the result of multiscale interaction involving both transients and stationary eddies. The evolution of UB has a profound impact on the weather and climate in East Asia, as a key precursor for winter cold surge and summer persistent precipitation in the region (S. Li et al., 2001; Park et al., 2011; Wang et al., 2010; Zhou et al., 2009). Understanding the key dynamical processes during the development and maintenance of UB has an important implication for the predictability of UB and the related extremes.

Previous studies found that blocking events over the ocean are commonly preceded by enhanced baroclinic wave activity along the upstream storm track (H. Nakamura & Wallace, 1990), most of which are accompanied by the development of explosive surface cyclogenesis (Alberta et al., 1991; Colucci, 1985; Tsou & Smith, 1990). The transients then trigger and maintain oceanic blocking through both barotropic and baroclinic processes that feed back to the incipient planetary ridges (Illari, 1984; Mullen, 1987; H. Nakamura & Wallace, 1993; Shutts, 1983; Tsou & Smith, 1990). In the case of UB, however, the background baroclinicity is weak and far away from the upstream ocean where storm track prevails (Vallis & Gerber, 2008), existing studies often assume UB to be a phenomenon originating from barotropic dynamics. For example, Takaya and Nakamura (2005) evaluated the barotropic synoptic eddy feedback and found it to account for 40% of the amplification of the ridge of UB (targeted at 57°N, 80°E), with the remainder coming from the quasi-stationary Rossby wave train propagating across the Eurasian continent. Luo et al. (2015) first
noted that a stronger than normal North Atlantic westerly wind or a positive phase of the North Atlantic Oscillation (NAO) tend to be conducive to UB downstream. By examining the horizontal wave activity flux and vorticity budget, Luo et al. (2016) further identified the quasi-stationary wave dispersion and propagation following the decay of the positive phase of the NAO to be the mechanism for the formation of the UB. This is corroborated by the dynamical modeling study of S. Li (2004), who investigated the dynamical linkage from the North Atlantic SST anomalies to UB and found it is the diabatic heating associated with the SST warming that drives the UB, with the eddy vorticity flux feedback only playing a secondary role. The more recent study of Shi et al. (2020) also agreed on the mechanism of the horizontal propagation, but they found little association with the NAO, instead that UBs often accompany the positive phase of the East Atlantic/West Russia pattern and the Scandinavian teleconnection pattern. On the other hand, several studies (Cheung et al., 2013; Hoskins & Hodges, 2002) noted the involvement of baroclinic processes, such as the buildup of baroclinic wave activity upstream of Urals during the formation phase of UB. Others (e.g., Pfahl et al., 2015) argued that the latent heat release during cloud formation could be an important negative potential vorticity (PV) source for the air parcels entering and contributing to the blocking system. These diverse views on the formation of UB motivate us to conduct a systematic budget analysis for UB during its different evolution phases.

It is thence our main goal here to build a comprehensive LWA diagnostics for UB, thereby, we can quantify the relative importance between the barotropic and baroclinic processes and that between the conservative and non-conservative wave processes throughout the lifecycle of UB. Historically, PV and enstrophy budgets have been used to diagnose the barotropic and baroclinic processes involved in the evolution of blockings (Colucci, 1985; Illari, 1984; Mullen, 1987; Shutts, 1983), but often suffer from the fact that the triple correlation term (i.e., eddy advection of the enstrophy) becomes non-negligible for finite amplitude disturbances like blockings, posing an accuracy issue and challenges to interpretation. Additionally, the conventional analysis (such as the wave activity flux of Takaya & Nakamura, 2001) is often derived from the small-perturbation assumption, which is inappropriate for blocking as it is often associated with the overturning of the PV contours (Solomon & Nakamura, 2012). Recently, Huang and Nakamura (2017) (hereafter HN17) introduced LWA and its budget, which generalize the small-amplitude theory to eddies of arbitrary amplitude with a closed budget. This new framework presents an advantage compared to the conventional Eulerian ones in terms of a more accurate satisfaction of the non-acceleration theorem for conservative processes, even for finite-amplitude disturbances. Here, we adopt this framework and extend it to account for the contribution from the diabatic heating and irreversible PV mixing, as such, a unified framework is constructed to put the barotropic and baroclinic terms, and the conservative and non-conservative terms on an equal footing.

By analyzing the 6-hourly ERA-Interim reanalysis data (Dee et al., 2011), we diagnose the baroclinic and barotropic processes and the conservative and non-conservative processes at different evolution phases of UB via LWA budget. This study illustrates the wave propagation and wave advection mechanisms, and reveals their distinct effects between the upstream and downstream sides of Urals; it also emphasizes the essential role of the baroclinic processes in UB formation and stagnation. The structure of this study has been organized as follows. LWA diagnostic framework and UB detection method are described in Section 2. The formation and evolution mechanisms of UB revealed by the LWA budget are presented in Section 3. The last section concludes and discusses opportunities for future investigations.

2. Methodology and Data

2.1. Definition of LWA and Its Budget

Finite-amplitude wave activity (FAWA, N. Nakamura & Zhu, 2010) is a hybrid Eulerian-Lagrangian quantity describing the area-integrated displacement of quasi-geostrophic potential vorticity (QGPV) from zonal symmetry, and it links the meandering of atmospheric circulation to eddy fluxes for both small and finite-amplitude disturbances. LWA is the local version of FAWA introduced by HN17 to quantify the longitude-by-longitude contributions of FAWA. In a spherical coordinate, LWA has been defined as a line integral from the equivalent latitude $\phi$ to the latitude of a given displaced PV contour $\phi + \Delta \phi$ (see Figure 1 of Huang & Nakamura, 2016):
\[ \Lambda'(\lambda, \phi, z, t) = -\frac{a}{\cos \phi} \int_0^\Delta \phi q_e(\lambda, \phi, \phi', z, t) \cos(\phi + \phi') d\phi \quad z > 0, \]  

(1)

Where \( a \) is the radius of the Earth, \((\lambda, \phi, z)\) denote longitude, latitude, and pressure pseudoheight \((z = -H \ln(p / p_0), p_0 = 1000hPa)\), and \( \Delta \phi \) is the local latitudinal displacement of the PV contour with respect to \( \phi \). \( q_e \) is the eddy component of QGPV, defined as the departure from a Lagrangian-mean eddy-free reference state, a would-be balanced, zonally symmetric state evolved from a given wavy condition through an adiabatic, frictionless process (N. Nakamura & Solomon, 2010; N. Nakamura & Zhu, 2010). This reference state can be achieved by unwrapping each PV contour to a zonally symmetric state in such a way that the area enclosed by the zonally symmetric PV is the same as the area poleward of the curvy PV contour. The latitude of the resultant zonally symmetric PV defines the equivalent latitude (denoted by \( \phi \)).

To avoid the complexity due to the orography in Urals, only the upper-level density-weighted LWA budget between approximate 5 km (Z1) and 16 km (Z2) is considered:

\[ \langle \cdot \rangle = \frac{\int_{z_1}^{z_2} e^{-z/H} \langle \cdot \rangle dz}{H_z}. \]  

(2)

Where \( H_z \) is the density weighted height between Z1 and Z2. In the spherical coordinate, the upper-level density-weighted mean LWA budget is formulated as follows:

\[ \frac{\partial}{\partial t} \langle \Lambda' \rangle \cos \phi = \frac{1}{a \cos \phi} \left( \frac{\partial}{\partial \lambda} \langle u_{\text{REF}} \Lambda' \rangle - \frac{a}{\cos \phi} \left[ \Delta \phi \int_0^\Delta \phi q_e(\phi + \phi') d\phi \right] + \frac{1}{2} \left( v_e^2 - u_e^2 - \frac{R}{H} e^{-z/H} \frac{\partial^2 \theta}{\partial \theta / \partial z} \right) \right) \]

(3)

Zonal LWA flux convergence

\[ + \frac{1}{a \cos \phi} \left( \frac{\partial}{\partial \phi} \langle u_e \rangle \cos^2(\phi + \phi') \right) \frac{\cos \phi}{H_z} \left[ e^{-z/H} \frac{\partial \theta}{\partial \theta / \partial z} \right]_{z=z_2} - \left[ e^{-z/H} \frac{\partial \theta}{\partial \theta / \partial z} \right]_{z=z_1} \]

(3)

Meridional eddy heat flux difference

\[ -\frac{1}{\cos \phi} \left( \int_0^{\Delta \phi} e^{-z/H} \frac{\partial}{\partial z} e^{-z/H} \frac{\partial \theta}{\partial \theta / \partial z} \cos(\phi + \phi') d\phi \right) + \langle \Lambda' \rangle > \cos \phi. \]  

(3)

where the subscript \( e \) denotes the departure from the reference state:

\[ q_e(\lambda, \phi, \phi', z, t) = q(\lambda, \phi + \phi', z, t) - q_{\text{REF}}(\phi, z, t). \]

(4)

\[ u_e(\lambda, \phi, \phi', z, t) = u(\lambda, \phi + \phi', z, t) - u_{\text{REF}}(\phi, z, t). \]

(5)

\[ v_e(\lambda, \phi, \phi', z, t) = v(\lambda, \phi + \phi', z, t). \]

(6)

\[ \theta_e(\lambda, \phi, \phi', z, t) = \theta(\lambda, \phi + \phi', z, t) - \theta_{\text{REF}}(\phi, z, t). \]

(7)

Readers are referred to HN17 for the detailed derivation of each term in the budget. One new development from HN17 is the explicit expression of the LWA sink/source due to diabatic heating vertical gradient. Diabatic heating is estimated as the residual of the thermodynamic equation (Holton, 1979), making use of the 6-hourly ERA-Interim data. The zonal LWA flux convergence includes three terms: the zonal LWA advection by the background reference flow \( u_{\text{REF}} \); the eddy LWA flux convergence due to zonal Stokes drift, which represents the "traffic jam effect" in a barotropic model for blocking (N. Nakamura & Huang, 2018); and the \( x \) component of the E-P flux convergence, which is usually much smaller in magnitude than the first two terms. In the limit of small perturbation, the zonal LWA flux in reference state dominates, while zonal eddy LWA flux by Stokes drift can be ignored. For perturbations of finite-amplitude, the eddy LWA flux by zonal
Stokes drift can play a significant role, acting in counter to the zonal LWA flux by $u_{\text{REF}}$ (N. Nakamura & Huang, 2018). The second and third terms of the right-hand side (RHS) of Equation 3 represent the meridional and vertical wave propagation effects from eddy momentum flux and eddy heat flux, respectively. The fourth term is the effect of diabatic heating as explained above. The residual term includes the irreversible PV mixing due to wave breaking and filamentation that often lead to wave activity dissipation, as well as the ageostrophic components and possible errors of the budget (see SI Section 1 and Figure S1 for how the upper-level winter climatological budget of LWA is maintained).

2.2. Blocking Detection Via Anticyclonic LWA

LWA is dynamically connected to blocking through the non-acceleration theorem (Huang & Nakamura, 2016; N. Nakamura & Zhu, 2010), that is, large-amplitude anomalies (or gradient reversal) in either 500 hPa geopotential height (e.g., Barnes et al., 2012) or potential temperature at the dynamical tropopause (e.g., Pelly & Hoskins, 2003) often developed at the expense of the westerlies (e.g., Tibaldi & Molteni, 1990). To identify blocking with LWA, the anticyclonic LWA has been proposed (Chen et al., 2015) to quantify the degree of meandering of the isoline toward the north. The anticyclonic QGPV-based LWA is defined similarly to Equation 1, except the line integral is taken only over the segment occupied by the negative 300 hPa QGPV anomalies. The procedures for UB events detection are as follows: (1) An anticyclonic LWA-based criterion (denoted by $\Lambda_A$) for UB is chosen so that it gives a very similar blocking statistics as that based on the TM90 index (see SI Section 2 and Figure S2 for details). (2) A blocking longitude is registered when the anticyclonic LWA value exceeds $\Lambda_A$ at any longitude within the Ural region (45°E−90°E, 35°N−82.5°N); (3) To be qualified for a blocking event, the contiguous blocking longitudes must exceed 12.5 deg in longitude and stay uninterrupted for at least 8 days. The blocking intensity is measured by the maximum anticyclonic LWA within the Ural region and the day of its occurrence is identified as the peak day of the UB event. As detailed in SI Section 2, the 300 hPa QGPV-based threshold ($\Lambda_A$) is chosen to be 200 m s$^{-1}$ and used consistently throughout this study. In this study, since our focus is the long-lasting blocking events, duration criterion of 8 days instead of the commonly used 5 days, is chosen here. In addition, to obtain clear spatial structures of the physical processes, only the cases whose daily center is confined within the range 60 ± 10°E are considered. We will leave the block-following analysis for future investigation.

Due to the stringent UB detection criteria above, only 20 winter UB events have been chosen for the composited UB evolution presented in Figure 1. The development of UB can be divided into three stages: early formation (Figure 1a), rapid growth (Figure 1b), and decaying stage (Figure 1c). In the whole lifespan of UB, the 500 hPa planetary ridge undergo a process of developing and strengthening northward, and then retreating and weakening southward. Correspondingly, LWA also undergoes a transition from strengthening to weakening, which is characterized by more compact centers compared to the corresponding geopotential height structure. In addition, LWA can also capture the troughs on either side of blocking, which would be
Geophysical Research Letters

even better illustrated by the cyclonic component of LWA (not shown here) (Chen et al., 2015). Moreover, the stationary Rossby wave on the western seaboard of the Europe manifests as another center of LWA.

2.3. Reanalysis Data

In this study, three-dimensional wind and temperature on 37 pressure levels at a 6-hour frequency from the European Center for Medium-Range Weather Forecasts ERA-Interim datasets (Dee et al., 2011) for 1979–2018 with a horizontal resolution of 1.5° × 1.5° are used to compute QGPV and diabatic heating rate. Then the \( q_{\text{REF}} \), is readily obtained from the monotonic relationship between the polar cap area bounded by the \( q_{\text{REF}} \) and the corresponding equivalent latitude (Butchart & Remsberg, 1986). Estimation of \( u_{\text{REF}} \) and \( \theta_{\text{REF}} \) are achieved by solving an elliptic equation relating \( u_{\text{REF}} \) to FAWA with no-slip boundary condition and thermal wind relation (See SI of HN17 for details). Note that all the 37 vertical levels are needed for solving the \( u_{\text{REF}} \) using successive over-relaxation method, although only the upper levels are considered for the subsequent analysis.

3. Results

3.1. Important Role of Baroclinic Process

To quantify the role of the baroclinic process in the development of UB, we compute the composite lag covariance between LWA and each term on the RHS of Equation 3. The time series is obtained by averaging LWA and its budget terms for the composited UB events over the corresponding domain highlighted by the red rectangles in Figure 1. The black solid line denotes the evolution of UB amplitude based on the domain averaged LWAcos\( \phi \) values. See the specific legend for terms represented by the corresponding line colors. Unit: m s\(^{-1}\) for LWAcos\( \phi \) and m s\(^{-2}\) for the LWA budget terms.

Figure 2. The lag covariance between the composited local wave activity (LWA) and the terms on the right hand side of Equation 3 for (a) the whole UB area; (b) the western domain; and (c) the eastern domain. The time series is obtained by averaging LWA and its budget terms for the composited UB events over the corresponding domain highlighted by the red rectangles in Figure 1. The black solid line denotes the evolution of UB amplitude based on the domain averaged LWAcos\( \phi \) values. See the specific legend for terms represented by the corresponding line colors. Unit: m s\(^{-1}\) for LWAcos\( \phi \) and m s\(^{-2}\) for the LWA budget terms.
During the decay phase of UB (at positive lag days), the differential eddy heat flux first plays a negative role in the LWA growth and then becomes positive at +7 days lag, suggesting a weak positive feedback of baroclinic eddies in extending the lifespan of UB. It is intriguing to see that the eddy momentum flux divergence (cyan) works in tandem with the differential eddy heat flux through the composite UB lifecycle with a slightly reduced amplitude. Note that within the quasi-geostrophic framework, these two eddy effects add up to the negative eddy QGPV flux integrated over the upper troposphere. It is somewhat expected that the diabatic heating term (purple) plays a damping role throughout the whole process, mostly through radiative cooling in the free atmosphere (see Figure S3). On the other hand, it is surprising to see that the residual term (gray) contributes positively to UB during its rapid growth stage—a puzzle to be revisited later.

As shown in Figure 1, the LWA maximum is centered upstream of Urals during the early formation stage of UB, then moves downstream during the establishment and decaying phase; and the LWA seems to dissipate faster upstream than downstream during the decaying phase. This differing behavior between the LWA upstream and downstream to the Urals prompts us to analyze the LWA evolution in these two regions separately. The lag covariance analysis in the upstream (western box) and downstream (eastern box) of Urals, respectively, reveals opposite roles of the differential eddy heat flux term, eddy momentum divergence term, and the residual term in these two regions (compare Figures 2b and 2c). Specifically, during the growth and maintaining stage, both eddy heat flux and eddy momentum flux work to boost the wave activity growth upstream, but at the expense of the wave activity growth downstream, while the residual term acts to concentrate wave activity toward downstream of the Urals. The zonal LWA flux plays an even more dominant role for the growth of the downstream wave activity, however, the upstream-downstream anti-symmetry is less evident for this term. The extended positive feedback from the differential eddy heat flux as noted in Figure 2a appears to operate only in the downstream box. In sum, both the zonal LWA advection and the residual terms are key to the downstream development of the blocking center manifested in LWA, with the differential eddy heat flux being important in the development of the upstream center and extending the lifespan of the downstream one. Many of the features discussed above can be carried over to short-lived UBs with a life span of 5–7 days, the results of which are shown in SI for comparison (see Figure S4), although the exact phasing of the processes may differ.

3.2. Downstream Development of UB

Figure 3 shows the composite evolution of UB diagnosed with the LWA budget. During the early formation stage, both the center of LWA and its tendency are all located in the upstream box (western box, Figure 3a1), indicating the preferential upstream growth of UB. As shown in the left column, the upstream growth of LWA results predominantly from the upward wave activity flux that corresponds to the differential eddy heat flux (Figure 3d1), while in a small part from the meridional eddy momentum flux divergence (Figure 3c1). Meanwhile, the background zonal flow ($u_{REF} > 0$ in the troposphere) tends to advect the LWA downstream (Figure 3b1), countering the effects of the eddy QGPV flux, which comprises the eddy heat flux (Figure 3c1) and eddy momentum flux components (Figure 3d1).

The rapid growth of the blocking downstream of Urals (Figure 3a2) is punctuated by the sharp concentration of the LWA downstream (Figure 3b2), likely through the eastward advection down the gradient of LWA by the eastward $u_{REF}$. Note that both the climatological winter LWA (Figure S1a) and the LWA anomalies during the formation stage have an eastward gradient over the Urals region. In the meantime, intensified transient eddy forcing via the eddy QGPV flux continues to sustain the wave activity level upstream (western box, Figures 3c2 and 3d2). The intensified differential eddy heat flux during the early formation and growth phases occurs to the north of Caspian Sea, consistent with the explosive cyclogenesis there prior to the onset of blocking noted in the previous studies (Alberta et al., 1991; Colucci, 1985; H. Nakamura & Wallace, 1990; Tsou & Smith, 1990).

The residual term has qualitatively a similar dipole effect as the zonal LWA advection term, dissipating the LWA upstream and growing it downstream (Figure 3f2). Provided that the residual term results predominantly from the dissipation of wave activity due to wave breaking, the negative/positive contribution upstream/downstream from the residual term reflects the tendency for the dissipation effect to compensate the eddy QGPV flux during the wave breaking stage of blocking (here mainly during day −3 to day 0).
Figure 3. Composites of local wave activity LWAcos\(\phi\) (contour, unit: m s\(^{-1}\)) and the wave activity budget terms (shading, unit: \(10^{-5}\) m s\(^{-2}\)) during the three different stages of UB. Each row from top to bottom corresponds to each of LWA tendency terms: (a) net tendency; (b) zonal LWA flux convergence; (c) meridional eddy momentum flux divergence; (d) meridional eddy heat flux difference; (e) diabatic heating; and (f) residual. The stippling indicates the regions where the signal is statistically significant at the 95% level based on Student's t test.
Recall that the eddy QGPV flux \((q_e v_e)\) is equivalent to the E-P flux divergence, that is, the negative of the combination of the second and third terms in the RHS of Equation 3. This is evidenced by the spatial correspondence between the dissipation dipole in Figures 3f1–3f2 and the eddy PV flux dipole \((-q_e v_e > 0\) upstream, \(-q_e v_e < 0\) downstream) as inferred from adding the panels of the differential eddy heat flux (Figures 3d1–3d2) to the corresponding ones of the eddy momentum flux divergence (Figures 3c1–3c2). Similar compensation between eddy PV flux and wave activity dissipation was also noted by Shutts (1983), though in an equivalent barotropic context.

At the decaying stage, as shown in the right column of Figure 3, the dipole-like structure of the budget terms between the two boxes becomes blurred. As the consequence of the attenuation of the baroclinic waves upstream (Figure 3d3) and the divergence of zonal LWA flux downstream (Figure 3b3), together with the persistent diabatic damping of LWA (Figure 3e3), UB gradually dissipates. Consistent with the damping effect of the diabatic term (Figure S3), a cooling center persists around 300 hPa level throughout the UB evolution, serving as a positive PV source above and negative PV source below it, with the former dominating the latter through the \(e^{-\gamma \lambda H}\) factor, resulting in a net damping on the wave activity associated with UB. Note that the effect of the residual term is also weakened at this stage, mainly manifested as a consumption of upstream wave activity.

In summary, the formation and evolution of UB can be considered as the result of the competition between the zonal LWA flux convergence (barotropic process) and the eddy QGPV flux, the latter being dominated by the differential eddy heat flux (baroclinic process). Meanwhile, the residual term, likely due to the dissipation of wave activity related to wave breaking, also plays an appreciable role in the downstream development of UB.

### 3.3. The Facet of Wave Propagation

To elucidate the formation and growth mechanisms of UB from the angle of conventional wave propagation, we reorganize the conservative terms in Equation 3 to distinguish the zonal advective flux of LWA and the generalized E-P flux as follows:

\[
\frac{\partial}{\partial t} \tilde{A} \cos \phi = -\nabla \cdot (F_{\text{adv}} + F_{\text{EP}}) + N,
\]

\[
F_{\text{adv}} = \left[ \left( u_{\text{REF}} A - \frac{a}{\cos \phi} \frac{\Delta \phi}{0} \right) \right. \left. u_q \cos \left( \phi + \phi' \right) \right] \cos \phi, 0, 0 \right]
\]

\[
F_{\text{EP}} = \left[ \frac{1}{2} \left( u_e^2 - u_e^2 \right) \right] \cos \phi, -v_{\text{REF}}, \left. \frac{\partial}{\partial \theta} \right|_0 \cos \phi, 0, 0, \frac{\partial}{\partial \phi} \left( \phi + \phi' \right), -e^{-\gamma \lambda H} \left. \frac{\partial}{\partial \phi} \right|_0 \cos \phi \right]
\]

\[
\nabla = \left[ \left. \frac{1}{\cos \phi} \frac{\partial}{\partial \lambda} \right|_0 \frac{\partial}{\partial \phi} \cos \left( \phi + \phi' \right), -e^{-\gamma \lambda H} \right. \frac{\partial}{\partial \phi} \left. \right|_0 \cos \phi \right]
\]

\(F_{\text{adv}}\) is the zonal advective flux of LWA, including that by the reference zonal wind and that by zonal Stokes drift. \(F_{\text{EP}}\) is the three-dimensional E-P flux (Trenberth, 1986), indicating the propagation of local wave activity. The divergence of \(F_{\text{EP}}\) corresponds to the northward eddy PV flux, while the divergence of the eddy component of \(F_{\text{adv}}\) corresponds to the eastward eddy PV flux as discussed in Shutts (1983), here in the context of LWA diagnostics. \(N\) is the shorthand notation for the non-conservative processes.

The respective roles of the convergence of \(F_{\text{adv}}\) and \(F_{\text{EP}}\) are depicted in Figure 4, in which there is a clear cancellation between them. In the initial stage, as shown in Figure 4a, anomalous upward flux of wave activity via the vertical component of \(F_{\text{EP}}\) appears upstream (See also Figure S5a for its vertical cross section),
meanwhile the anomalous horizontal wave activity flux converges into the western box from the south, reflecting variations in the Mediterranean storm track (Whittaker & Horn, 1984). Notably, there is a wide swath of wave fluxes emanating from the mid-latitude Atlantic and taking an arched path toward the Urals (Figure 4a), implying a possible effect of the Rossby waves originating from North Atlantic on the UB formation (S. Li, 2004; Luo et al. 2016). In the interim, the zonal convergence of LWA advection \((F_{\text{adv}})\) acts to extract wave activity from the western box and deposit to the eastern box (Figure 4d). As such, the total zonal advection constitutes the most important mechanism for the downstream development of UB. During the rapid growth stage, LWA advection effect intensifies sharply (Figure 4e), transferring wave activity from the western side to the eastern side of 60°E and giving rise to a large-scale wave activity convergent-divergence dipole, only the southern tip of which protrudes toward the Urals. The accumulation of wave activity on the eastern side is relayed back to the western side by wave propagation (i.e., \(F_{\text{EP}}\)) through both vertical and horizontal pathways (Figure 4b, see also Figures S5b and S5e). The essential role of the vertical wave propagation is implicative of the importance of vertical coupling during the rapid growth stage. At the decaying stage, both advection and propagation effects decay and retreat northward away from the Urals region (Figures 4c and 4f), while the diabatic damping (Figure 3e3) and dissipation (Figure 3f3) dominate the tendency of wave activity over the region. Therefore, it is the wave propagation (i.e., the vertical and horizontal components of the \(F_{\text{EP}}\)) that dominates the initial growth of the upstream UB and it is the barotropic advection of wave activity that is responsible for the downstream development of UB. Caution should be exercised while comparing this result with the apparently conflicting notion of Luo et al. (2016), who emphasized the importance of horizontal wave dispersion in the development of UB. One should keep in mind that Luo et al. (2016) only considered the barotropic component of the wave activity flux of Takaya and Nakamura (2001) and the Takaya-Nakamura flux does not distinguish the wave activity advection from wave activity propagation.

4. Conclusions and Discussion

By examining the upper-tropospheric LWA budget using the ERA-Interim 6-hourly reanalysis data, this study illustrates the wave propagation and wave advection mechanisms during the evolution of UB. The result reveals distinct effects of these two wave mechanisms between the upstream and downstream sides.
of Urals; it also underlines the importance of the baroclinic processes in block initiation and stagnation. More specifically,

1. At the formation stage of UB, local baroclinic growth helps initiate the LWA (tendency) anomaly upstream of Urals with the remote baroclinic sources from mid-North Atlantic and the Black Sea feeding wave activity toward the initial block. Meanwhile, the barotropic processes, mainly through the zonal advection of LWA, disperse the wave activity to the downstream of Urals.

2. At the rapid growth stage, the zonal advection intensifies sharply, extracting wave activity from upstream and depositing it downstream of the Urals, while the wave activity upstream is being replenished by the enhanced local baroclinic growth as well as the retrogressive wave propagation across the Urals and the northward propagation from the Caspian Sea. The net effect of the competition between wave advection and wave propagation is the rapid intensification of UB with its center shifting toward the downstream of the Urals. The wave propagation mechanism, especially the baroclinic component of it, plays an essential role in the stagnation of the system—the key characteristic of blocking. During this stage, the irreversible dissipation of wave activity appears to assist the advection mechanism in the downstream development of UB.

3. At the decaying stage, as both wave advection and propagation mechanisms are attenuated, the diabatic damping due to the radiative cooling gradually takes over, leading to the demise of UB.

Our LWA budget analysis is the first attempt to depict comprehensively the wave activity evolution throughout the lifecycle of UB, accounting for not only the barotropic and conservative processes, but also the baroclinic terms and non-conservative processes. This effort evinces a nuanced compensation between wave propagation and wave advection, and that between the eddy QGPV flux and the downgradient dissipation at different stages of the UB development. The complex interplay among these factors seems to advise against the interpretation of UB solely based on barotropic thinking (Luo et al., 2016; Takaya & Nakamura, 2005).

In view of the distinct mechanisms manifested between the upstream and downstream of the Urals and the downstream development during the fast-growing phase of UB, it is tempting to draw parallels between UB and wave packets. However, a more discerning analysis is needed to determine if UB is a type of wave packets. Our budget analysis also suggests a possible compensation between the eddy PV flux and the irreversible mixing of the PV due to wave breaking during the maturing stage of UB, as required by the major balance among the adiabatic processes (the diabatic wave damping does not have a dipolar structure), while this assertion remains to be verified by a direct estimate of the irreversible dissipation effect in the budget. Last, we must admit that this is only a beginning to examine blocking in the light of LWA, further development of the wave activity budget along the line of decomposing the LWA into different time and/or spatial scales may facilitate a better comparison with the conventional analysis of blocking.

A growing number of studies suggested that the Atlantic SST anomalies and sea ice melting over the Barents-Kara sea can lead to more frequent and longer lasting anticyclonic circulation over the Urals and hence, more UB (S. Li, 2004; Luo et al., 2018; Mori et al., 2014; Xue et al., 2017; Yao et al., 2017). However, the exact mechanisms of how a thermal perturbation may impact the dynamics of blocking remain unclear. The analysis here shows a salient dipole-like structure associated with the wave activity propagation with one pole centered right around the Barents-Kara sea during the evolution of UB (Figures 2 and 3). It should be a worthwhile effort to focus on the surface forced LWA evolution, such as that by Barents-Kara sea ice melting.

**Data Availability Statement**

The European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim data are accessible from [https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/](https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/).

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