Energetics of the Western Hemisphere Circulation Pattern

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ABSTRACT

The Western Hemisphere (WH) circulation pattern, identified by self-organizing maps cluster analysis, is a low-frequency atmospheric regime that influences the fluctuations of large-scale circulation over the North Pacific–North American–North Atlantic areas. The reanalysis datasets from ECMWF are used to estimate the energetics of the WH pattern in this study. The composite results based on monthly WH events reveal that the kinetic energy (KE) associated with the WH pattern is maintained through the barotropic conversion from the climatological-mean westerlies, mainly in the Atlantic jet exit regions. The KE could also be gained through the barotropic feedback forcing from transient eddies. The corresponding baroclinic conversion of available potential energy (APE) from the climatological-mean state, which contributes most efficiently to the energy maintenance of the WH pattern, is obvious in the middle and lower troposphere, owing to the thermal contrast of the colder continent and warmer ocean over the North America–North Atlantic sector. The baroclinic conversion associated with the heat flux on the climatological temperature gradient is consistent with the southwestward-tilting height anomalies from 850 to 500 hPa. The baroclinic feedback from transient eddies contributes negatively to the energy conversion and destroys the maintenance of the WH pattern.

1. Introduction

Previous studies demonstrated that there are several large-scale teleconnection patterns contributing to Northern Hemisphere wintertime low-frequency variability (Wallace and Gutzler 1981, hereafter **WG81**; Horel 1981; Barnston and Livezey 1987). Among these patterns, the North Atlantic Oscillation (NAO; Walker and Bliss 1932; Hurrell et al. 2003), which appears as a dipole structure with one center over Greenland and the other in midlatitudes, is the most prominent pattern in the North Atlantic. The western Pacific (WP) teleconnection pattern (**WG81**) and the Pacific–North American (PNA) teleconnection pattern (**WG81**) explain most low-frequency fluctuations over the North Pacific and North America.

It is indicated in previous studies that the low-frequency patterns can drain kinetic energy (KE) from the climatological-mean flow through barotropic instability

mainly in the jet exit areas (Simmons et al. 1983; Schubert 1986; Nakamura et al. 1987). The PNA pattern, with its subtropical anomalies near the North Pacific jet exit regions, obtains kinetic energy more efficiently than the WP pattern and the NAO pattern, which is located near the North Pacific jet core and is relevant to the weaker North Atlantic jet, respectively (Nakamura et al. 1987). The feedback forcing from transient eddies is the dominant mechanism that contributes to the growth and maintenance of the NAO pattern (e.g., Lau and Nath 1991; Feldstein 2003). The external forcing related to the tropical anomalies (Horel and Wallace 1981; Hoskins and Karoly 1981; Simmons 1982; Trenberth et al. 1998) and eddy–mean flow feedback (Lau 1988; Branstator 1992; Feldstein 2002; Orlanski 2005) also account for the maintenance of the PNA pattern. It is suggested that the barotropic feedback from transient eddies can maintain the WP pattern mainly in the upper troposphere (Lau 1988; Lau and Nath 1991).

Many studies emphasized barotropic processes associated with synoptic waves and time-mean flow, since the vertical structure of teleconnection patterns seem to be equivalent barotropic (**WG81**; Blackmon et al. 1979; Hsu and Wallace 1985). However, a baroclinic structure, with a westward phase tilt with height, is found in the

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FIG. 1. (a) The 500-hPa WH pattern from Bao and Wallace (2015); (b) monthly time series of the standardized WH index (red line) and the PC (blue line) of REOF 7 of the Northern Hemisphere wintertime 500-hPa height fields from 1957/58 through 2016/17. The contour interval is 25 m in (a); red (blue) contours denote positive (negative) values; the zero contours are omitted. The correlation (R) of WH index with PC 7 is shown on the right side in (b).

PNA pattern (Black and Dole 1993; Black 1997) and the WP pattern (Linkin and Nigam 2008; Tanaka et al. 2016), which means that baroclinic processes are also important. Schubert (1986) indicated that although barotropic processes still account for the major portion of the total energy, the baroclinic energy conversion could make a substantial contribution to maintain the low-frequency (greater than 45 days) variability. Moreover, Tanaka et al. (2016) investigated the energetics of the WP pattern and found the baroclinic conversion from the climatological-mean flow, because of the relevant heat fluxes and the significant contrasts of the time-mean temperature, contributes to maintain the WP pattern with the highest efficiency.

Recently a new low-frequency teleconnection pattern was identified by using the self-organizing maps method on the 10-day low-pass-filtered 500-hPa height field (Bao and Wallace 2015; C2 in their Fig. 2). This pattern appears to be a mode suggestive of an Alaska anticyclone anomaly with a downstream wave train extending over North America and the North Atlantic (Fig. 1a; and C2 in Fig. 2 of Bao and Wallace 2015). Since the wave train crosses the North Pacific–North America–North

Atlantic sector, this pattern is referred to as the Western Hemisphere (WH) circulation pattern in Tan et al. (2017). The WH pattern provides us a unique mode that accounts for variance over the whole North Pacific–North America–North Atlantic region. Bao and Wallace (2015) revealed that the WH pattern has comparable external-to-total variance ratio (dividing the squared distance between a cluster's centroid and the centroid of the entire dataset by the mean squared distance between the individual maps in that cluster and the centroid of the entire dataset) with the NAO and PNA patterns in cluster analysis during the winters from 1957/58 through 2013/14.

Wave-maintained mechanisms that contribute to the formation and maintenance of the WH pattern were studied in Tan et al. (2017). Their results indicate that although the WH pattern appears as a stationary Rossby wave train propagating from the North Pacific to the North Atlantic, the propagation of quasi-stationary Rossby waves cannot fully account for the formation and maintenance of the WH pattern. The trough over the North Atlantic is mainly maintained by the eddy–mean flow feedback, resembling the maintenance of the

NAO. The downstream development of synoptic waves from the North Pacific to the North Atlantic is also an important process that helps maintain the WH pattern, particularly helping to extend the trough anomaly eastward into the North Atlantic region. Since the south–north dipole structure and the zonal thermal contrast (cooler continent and warmer ocean during wintertime) over the North Atlantic in the WH pattern resemble those over the North Pacific in the WP pattern, baroclinic processes mentioned in Tanaka et al. (2016) may also account for the maintenance of the WH pattern. In this study, we investigate the energy conversion associated with the WH pattern and assess the efficiency of each term quantitatively. In the view of energetics, we could understand the processes, which contribute to maintain the WH pattern, more systematically and completely.

This paper is organized as follows. Section 2 presents the details of the data and methods. Section 3 demonstrates the flow features associated with the WH pattern. In section 4, we evaluate energetics of the WH pattern. A summary and discussion are provided in section 5.

2. Data and methods

a. Dataset

All computations in this work are based on the daily and monthly mean fields from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) and ECMWF interim reanalysis (ERA-Interim; Dee et al. 2011) datasets. The wintertime denotes the period from December through February (DJF) in this work. A continuous 60-winter dataset is obtained by combining the ERA-40 dataset from September 1957 through December 1978 with the ERA-Interim dataset from January 1979 through March 2017. The combined dataset is interpolated to a $2.5^\circ \times 2.5^\circ$ grid and 13 vertical pressure levels from 1000 to 100 hPa. To get the daily or monthly anomalies, the seasonal cycle, obtained by calculating the time mean values for each calendar day or month averaged over 1957–2017, is subtracted at each grid point. The wintertime monthly anomalies are obtained by subtracting the climatological seasonal cycle.

b. WH pattern index

The WH pattern (Fig. 1a) is identified from cluster analysis using self-organizing maps on the 10-day low-pass-filtered 500-hPa geopotential height (Z500) anomalies [Fig. 2 (C2) in Bao and Wallace 2015]. The long-time linear trend in height field is first subtracted. We project the DJF monthly Z500 anomalous fields

onto the WH pattern (Fig. 1a). The standardized time series of the spatial regression coefficients of Z500 anomalies onto the WH pattern are defined as the WH index (WHI).

We identify a month when the WHI exceeds 1.0 as a strong positive WH event. In total, 29 positive WH months are selected. Similarly, we obtain 28 strong negative WH events when the WHI is below -1.0 . The positive and negative WH monthly events are shown in Table S1 in the online supplemental material. The WH events are mainly used for composite analysis to estimate various anomalies associated with the positive and negative WH pattern.

c. Formulas for energetics analysis

According to previous works (Hoskins et al. 1983; Simmons et al. 1983; Tanaka et al. 2016), barotropic energy conversion [or KE conversion (CK)] from the climatological-mean flow into the monthly anomalies has been estimated in Eq. (1):

$$CK = \frac{v'^2 - u'^2}{2} \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) - v' u' \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right). \quad (1)$$

Here, u and v denote the zonal and meridional wind components, respectively. The overbars and primes in this and following equations denote climatological-mean quantities and monthly mean anomalies, respectively. The positive CK means that KE, defined in Eq. (6), is converted from the climatological-mean flow into the monthly anomalies.

Baroclinic energy conversion (CP), which indicates the available potential energy (APE) converted from the basic state to the monthly anomalies, is estimated by Eq. (2), referring to Kosaka and Nakamura (2006):

$$CP = -\frac{R}{p\sigma} \left(u' T' \frac{\partial \bar{T}}{\partial x} + v' T' \frac{\partial \bar{T}}{\partial y} \right), \quad \text{and} \quad (2)$$

$$\sigma = \frac{R\bar{T}}{C_p p} - \frac{\partial \bar{T}}{\partial p}. \quad (3)$$

The variable T denotes the temperature and p denotes the pressure level; σ , which denotes the stability parameter, is calculated in Eq. (3), where C_p and R denote the specific heat at constant pressure p and the gas constant, respectively.

Tan et al. (2017) emphasized the importance of feedback forcing from transient eddies in the maintenance of the WH pattern. The KE and APE gains for the monthly WH pattern due to feedback of high-frequency transient eddies can be obtained as in Tanaka et al. (2016):

TABLE 1. Efficiency (day^{-1}) of each energy conversion term, including CK, CP, CK_{HF} , and CP_{HF} . The efficiency indicates how fast a particular term alone could replenish the total energy ($\text{KE} + \text{APE}$) according to the composited monthly mean anomalies averaged over WH events. Positive (negative) WH means the efficiency calculated over the positive (negative) WH events. Positive (negative) values denote the positive (negative) contribution of corresponding conversion term to the maintenance of the WH pattern.

	Positive WH	Negative WH
Barotropic conversion (CK)	0.008	0.019
Baroclinic conversion (CP)	0.210	0.187
Barotropic eddy forcing (CK_{HF})	0.039	0.060
Baroclinic eddy forcing (CP_{HF})	−0.032	−0.038

$$\text{CK}_{\text{HF}} = -u' \left[\frac{\partial(u''u'')'}{\partial x} + \frac{\partial(u''v'')'}{\partial y} \right] - v' \left[\frac{\partial(u''v'')'}{\partial x} + \frac{\partial(v''v'')'}{\partial y} \right], \quad \text{and} \quad (4)$$

$$\text{CP}_{\text{HF}} = -\frac{RT'}{p\sigma} \left[\frac{\partial(u''T'')'}{\partial x} + \frac{\partial(v''T'')'}{\partial y} \right]. \quad (5)$$

The double primes denote the 10-day high-pass-filtered components associated with transient eddies, which are extracted by a 10-day high-pass Lanczos filter. In the following texts, the KE and APE conversions associated with transient eddies, defined as Eqs. (4) and (5), are referred to as barotropic feedback CK_{HF} and baroclinic feedback CP_{HF} , respectively.

The total energy KE and APE are estimated by Eqs. (6) and (7), respectively, as in Kosaka and Nakamura (2006):

$$\text{KE} = \frac{u'^2 + v'^2}{2}, \quad \text{and} \quad (6)$$

$$\text{APE} = \frac{RT'^2}{2p\sigma}. \quad (7)$$

The conversion terms by 10-day low-pass-filtered fields are also calculated to compare with the monthly mean fields. In that situation we define the positive (negative) WH days when the 10-day low-pass daily WH index is above 1.0 (below −1.0) and obtain the similar spatial distributions of the conversion terms with slightly larger amplitudes. It doesn't qualitatively affect the results of the conversion efficiency, which are shown in Table 1 and discussed in section 4. In this work, only the results by the monthly mean fields are shown for better comparing with the energetics analysis of the WP pattern (Tanaka et al. 2016).

3. Flow features associated with the WH pattern

To obtain the dominant modes of variability in wintertime Northern Hemisphere, a rotated empirical

orthogonal function (REOF) analysis is applied to the DJF monthly anomalous field of Z500 over the domain poleward of 20°N from 1957/58 through 2016/17. To calculate the REOF modes, Z500 anomalies are weighted by the square root of cosine of latitude. In this REOF analysis, 10 unrotated EOFs were retained, which can explain more than 80% of total variance.

The results of partial REOFs are shown in Fig. 2 by calculating the regression of Z500 anomalies on the standardized principal component (PC) of the corresponding REOFs, and the title of each panel indicates the corresponding ranking. The fractional variance is shown at the top-right side. The first three REOFs resemble the NAO, PNA, and WP patterns, respectively. The result of REOFs is similar to that in previous works (Barnston and Livezey 1987; Feldstein 2000). In addition, we found that the seventh REOF mode (Fig. 2d) is a large-scale pattern that resembles the WH pattern (Fig. 1a). Figure 1b shows the monthly time series of WHI (red) and the standardized PC of REOF 7 (blue). The correlation coefficient between the two time series is 0.84, which is significant at the 95% confidence level based on the Student's *t* test. This result indicates that, though identified by nonlinear cluster analysis, the WH pattern can be reproduced by a linear method (like REOFs) and is robust in low-frequency variabilities whether using the linear or nonlinear analysis method.

Figure 3 shows the composite 250-, 500-, and 850-hPa geopotential height anomalies for monthly positive WH events (listed in Table S1). At the 250-hPa level, the positive WH pattern shows a dipole structure over the North Pacific, with negative and positive height anomalies over the southward and northward flanks of the exit of the Pacific jet, respectively. In addition, the dipole structure over the North Atlantic shows an obvious negative height anomaly, extending from North America to the North Atlantic, with a positive height anomaly centered on the Atlantic jet exit region. In agreement with Tan et al. (2017), the North Atlantic jet is enhanced and shifts northward when the positive WH pattern is significant at the 250-hPa level. Comparing the composite height anomalies at three levels, the WH pattern appears as a barotropic structure from 500 to 250 hPa according to the similar spatial distributions, which was also mentioned in Tan et al. (2017). However, we found that the phase of the composite anomalous trough over the North Atlantic tilts southward and westward with height in the lower troposphere, when comparing the height anomalies at the 850- and 500-hPa levels. This vertical structure, similar to the WP pattern shown in Tanaka et al. (2016), suggests that baroclinic processes could influence the growth and maintenance of the WH pattern. The relevant processes will be studied in the

FIG. 2. Regressions of DJF monthly 500-hPa geopotential height anomalies on the standardized PCs of corresponding REOFs. The contour interval is 15 m in each frame; red (blue) contours denote positive (negative) values; the zero contours are omitted. Shading indicates statistical significance at the 95% level based on a two-sided t test. The title of each panel indicates the corresponding ranking, and the fractional variance is shown on the top-right side.

following section. The negative WH pattern shows a similar structure compared to the positive phase, except for the opposite height anomalies.

4. Energetics analysis of the WH pattern

To investigate the maintenance mechanisms of the WH pattern in the view of energetics, the energy conversion terms associated with the composite anomalies of the WH events are quantified according to the formulas provided in section 2. To avoid the influence of flow anomalies irrelevant to the WH pattern on the energy conversion terms, we calculate the composite anomalies associated with the WH events before computing the energy conversion terms referring to the

procedure in Tanaka et al. (2016). For the transient eddy feedback terms, the high-frequency transient heat and momentum fluxes associated with the WH events are composited. The spatial distribution of each energy conversion term, obtained on the basis of the composite results of the positive events, is shown in the subsequent analysis, and the results according to the negative WH events are similar.

The 250-hPa CK, which indicates the barotropic energy conversion from the climatological-mean flow into the monthly anomalies associated with the positive WH pattern, is shown in Fig. 4a. There are obvious positive CK signals over the northern flank of the Pacific jet exit regions. In addition, the positive CK signals are significant and extend zonally from the northern flank of the

FIG. 3. Composite geopotential height anomalies at the (a) 250-, (b) 500-, and (c) 850-hPa levels (contoured every 25, 15, and 10 m s^{-1} , respectively). Red (blue) contours denote positive (negative) values; the zero contours are omitted. The composites are averaged over positive WH events listed in Table S1. Black contours in (a) denote the 250-hPa DJF climatological-mean zonal winds (contoured every 10 m s^{-1} , beginning at 30 m s^{-1}).

Atlantic jet core areas to the jet exit areas. There are also positive CK signals over the southern flank of the Atlantic jet exit regions. The spatial distribution of CK over the North Atlantic is similar to the result associated with the WP pattern (Tanaka et al. 2016), which mainly exist in the North Pacific. Figures 4b and 4c show the spatial distribution of 250-hPa CKx [the first term of CK in Eq. (1)] and CKy [the second term of CK in Eq. (1)], respectively. CKx (CKy) indicates the CK signals associated with the zonal (meridional) shear of the background basic jet. Figure 4b shows that the CKx is obvious and contributes positively to the CK signals

over the northern flank of the Pacific jet exit areas and the northern and southern flanks of the Atlantic jet exit areas, where the zonal wind anomalies, denoted by arrows, and the zonal wind shear of the climatological-mean jet are both strong. CKy contributes positively to CK on the northern portion of the Atlantic jet core over the east coast of North America (Fig. 4c), where the anomalous northwesterly is obvious and yield anomalous advection of climatological westerly momentum across the meridional shear of the Atlantic jet.

Since both the baroclinic structure and the smaller stability parameter, associated with the WH pattern,

FIG. 4. (a) Composite 250-hPa barotropic KE conversion CK (shading; see scale bar at bottom; $\text{m}^2 \text{s}^{-3}$). The composites are averaged over positive WH events. (b) As in (a), but for the CK related to the zonal shear of the climatological-mean jet (CKx). (c) As in (a), but for the CK related to the meridional shear of the climatological-mean jet (CKy). Arrows in (b) and (c) denote the composites of 250-hPa wind anomalies averaged over 29 positive WH months. The scale of arrows is given at the bottom (m s^{-1}). Black contours in (a)–(c) denote 250-hPa DJF climatological-mean zonal winds (contoured every 10 m s^{-1} , beginning at 30 m s^{-1}).

FIG. 5. (a) Composite baroclinic APE conversion CP (shading; see scale bar at bottom; $\text{m}^2 \text{s}^{-3}$) and temperature anomalies (contours; interval: 1 K) at the 500-hPa level. (b) As in (a), but for the CP related to the zonal gradient of the climatological-mean temperature (CPx; shading) and zonal wind anomalies (contours; interval: 2 m s^{-1}). (c) As in (a), but for the CP related to the meridional gradient of the climatological-mean temperature (CPy; shading) and meridional wind anomalies (contours; interval: 2 m s^{-1}). (d)–(f) As in (a)–(c), but for the 850-hPa level; the interval of contours in (d)–(f) is 1 K, 1.5 m s^{-1} , and 1.5 m s^{-1} , respectively. The composites are averaged over positive WH events. Red (blue) contours denote positive (negative) values; the zero contours are omitted. Brown contours in the top (bottom) panels denote 500-hPa (850-hPa) DJF climatological-mean temperature (contoured every 10 K, beginning at 240 K).

exist in the middle and lower troposphere, the baroclinic conversion CP, which means the conversion of APE from the climatological state to monthly anomalies, is more significant in the lower level. In the lower and middle troposphere, there is a cold anomaly extending from North America to the North Atlantic, with a warm anomaly centered on the Aleutian Islands, associated with the positive WH pattern (Figs. 5a,d). The wind anomalies shown in Fig. 5 are consistent with the height anomalies of the WH pattern at the

850- and 500-hPa levels (Figs. 3b,c). The first and second terms of CP in Eq. (2), are referred to as CPx and CPy, which associated with the climatological-mean zonal and meridional temperature gradients, respectively. Figures 5a–c show the distributions of CP, CPx, and CPy associated with the positive WH pattern at the 500-hPa level, respectively. Positive CP maxima are evident to the southeast of the Aleutian Islands and over the northwest area of North America. In addition, there are two positive CP centers located

over the North Atlantic, near the east coast of North America.

The northern and southern positive CP signals over the North Atlantic are mainly dominated by the CPx and the CPy, respectively. Figure 5b shows that the northern CP maximum to the south of Greenland is mainly enhanced due to the strong zonal climatological-mean temperature gradient, indicating the thermal contrast between the colder continent and the warmer ocean in wintertime. And the westerlies (denoted by contours in Fig. 5b) acting on this temperature gradient generate cold advection to help maintain the cold anomalies over the North Atlantic (Fig. 5a), resulting in the large positive CPx signals (Fig. 5b). Similarly, around the southern CP maxima over the North Atlantic, APE contributed by CPy is converted mainly through the poleward heat flux acting on the climatologically meridional temperature gradient (Fig. 5c) and help maintain the local warm anomalies in the mid-latitudes over the North Atlantic (Fig. 5a).

The positive CP anomalies over the North Pacific are contributed to both by the CPx and CPy (Figs. 5b,c). The CPx signals appear as a zonal strip over the North Pacific (Fig. 5b), while the CPy signals present in a local maxima area due to the poleward heat flux on the climatological-mean temperature gradient (Fig. 5c). The positive CP signals over the northwest of North American continent, where northerlies are significant associated with the positive WH pattern, are mainly contributed to by the cold advection on the climatological meridional temperature gradient (Fig. 5c).

In the lower troposphere (Figs. 5d–f), the structure of positive CP signals, with relatively smaller strength due to the smaller wind anomalies, is similar to that at the 500-hPa level. The CP distribution associated with the WH pattern bears an analogous structure over the North Atlantic compared to the WP pattern (Tanaka et al. 2016). The poleward and westward heat flux are consistent with the westward- and southward-tilting height anomalies associated the WH pattern from 850 to 500 hPa, respectively. The above results indicate that the baroclinic conversion is an important process to maintain the WH pattern, through gaining energy from basic state to maintain the corresponding temperature anomalies.

Tan et al. (2017) showed the importance of the synoptic waves to the maintenance of the WH pattern. Next, we evaluate the barotropic and baroclinic feedback forcing from transient eddies on the WH pattern by the Eqs. (4) and (5).

The barotropic feedback from synoptic waves (CK_{HF}) is estimated at the 250-hPa level (Fig. 6a), where the monthly wind anomalies and the high-frequency wind

anomalies both tend to be larger than those at other levels. Consistent with Tan et al. (2017), upper-tropospheric CK_{HF} contributes positively to the maintenance of the WH pattern by acting to increase KE over the central North Pacific, the Gulf of Alaska, and the North Atlantic (Fig. 6a). By calculating the first (CK_{HF1}) and second (CK_{HF2}) terms of CK_{HF} in Eq. (4), it is indicated that CK_{HF} signals over the North Pacific and the North Atlantic are mainly contributed to by CK_{HF1} (Fig. 6b), which are related to the convergence of eddy westerly momentum flux. Moreover, CK_{HF} over the Gulf of Alaska is strengthened due to CK_{HF2} (Fig. 6c), which is associated with the convergence of eddy southerly momentum flux. It is shown in Fig. 6d that the anomalous westerlies over the North Atlantic, associated with the positive WH pattern, could be strengthened by the anomalous convergence of eddy westerly momentum flux. The anomalous westerlies and convergence could jointly contribute to the positive CK_{HF1} signals. The situation of the zonal wind anomalies and the convergence of eddy westerly momentum flux is opposite over the North Pacific comparing to the North Atlantic and can also enhance the positive CK_{HF1} signals (Fig. 6d). Similarly, the anomalous divergence of the eddy southerly momentum flux associated with the positive WH pattern, which reinforces the anomalous northerlies over the Gulf of Alaska contribute positively to CK_{HF2} signals (Fig. 6e).

In contrast to CK_{HF} , the CP_{HF} , with larger magnitude in the lower and middle troposphere, contributes negatively to the maintenance of the WH pattern (Figs. 7a,b). The negative CP_{HF} signals are mainly located over the Gulf of Alaska, the northeastern region of North America and to the south of Greenland. There are anomalous convergence and divergence of the eddy heat flux where the cold and warm anomalies are significant to the north and south of the storm-track axis over the North Atlantic (Figs. 7c,d), respectively. In this situation, transient eddies tend to weaken the thermal anomalies and relax anomalous temperature gradient associated with the WH pattern. As shown in previous studies (Lau and Nath 1991; Tanaka et al. 2016), the anomalous eddy heat flux is generally acting to destroy the temperature anomalies associated with the low-frequency pattern and tend to render the monthly anomalies less baroclinic. This mechanism could also interpret the result of CP_{HF} associated with the WH pattern. Different from the baroclinic conversion from the basic state, the baroclinic feedback forcing from synoptic waves contribute negatively to the maintenance of the WH pattern.

To estimate the energy conversion terms for the WH pattern quantitatively, we integrated each energy

FIG. 6. (a) Composite barotropic KE conversion CK_{HF} at the 250-hPa level (shading; see scale bar at bottom; $m^2 s^{-3}$). (b) As in (a), but for the CK_{HF} related to the flux of westerly momentum associated with transient eddies (CK_{HF1}). (c) As in (a), but for the CK_{HF} related to the flux of southerly momentum (CK_{HF2}). (d) Composite 250-hPa divergence of westerly momentum associated with transient eddies (shading; see scale bar at bottom; $m^2 s^{-3}$) and zonal wind anomalies (contours; interval: 4 $m s^{-1}$). (e) As in (d), but for the 250-hPa divergence of southerly momentum (shading) and meridional wind anomalies (contours; interval: 2 $m s^{-1}$). The composites are averaged over positive WH events. Solid (dashed) contours denote positive (negative) values in (d) and (e); the zero contours are omitted. Black contours in (a)–(c) indicate 250-hPa DJF climatological-mean zonal wind (contoured every 10 $m s^{-1}$, beginning at 30 $m s^{-1}$).

conversion term over a three-dimensional domain. The horizontal domain includes the entire extratropical Northern Hemisphere (20° – $90^{\circ}N$), and the vertical domain ranges from the surface to 100 hPa. Since there is not surface pressure variable in ERA-40 dataset, the surface pressure map associated with the WH pattern is composite from the WH events from 1979/80 through 2016/17. The integrated energy conversion terms are divided by the sum of KE and APE [evaluated by Eqs. (6) and (7)], which denote the total energy associated

with the WH pattern, to obtain the efficiency of each term (Table 1). The efficiency indicates how fast a particular term alone could replenish the total energy associated with the WH pattern. The positive (negative) efficiency suggests that the corresponding term contributes positively (negatively) to the maintenance of the monthly WH events.

Comparing the different terms listed in Table 1, the baroclinic energy conversion CP contributes positively to the total energy with the highest efficiency, and

FIG. 7. Composite baroclinic APE conversion CP_{HF} at the (a) 500- and (b) 850-hPa levels (shading; see scale bar at bottom; $m^2 s^{-3}$). Composite divergence of temperature flux associated with transient eddies (shading; see scale bar at bottom; $m^2 s^{-3}$) and temperature anomalies (contours; interval: 1 K) at the (c) 500- and (d) 850-hPa levels. Solid (dashed) contours denote positive (negative) values in (c) and (d); the zero contours are omitted. The composites are averaged over the positive WH events.

replenishes the total energy within about 5 days during both positive and negative WH events. This result suggests the importance of the baroclinic conversion from the basic state to maintain the WH pattern. The barotropic feedback from transient eddies CK_{HF} has the

second highest efficiency and is also important to the maintenance of the WH pattern, in agreement with the results in Tan et al. (2017). The baroclinic feedback from transient eddies CP_{HF} , significant in the middle and lower troposphere, contributes negatively and can

dissipate the total energy of the WH pattern alone within about a month. Compared to the energetics of the WP pattern (Table 2 in Tanaka et al. 2016), the barotropic conversion CK associated with the WH pattern is smaller and has the lowest positive efficiency compared to other conversion terms. The strength and horizontal shear of the Atlantic jet is smaller than that of the Pacific jet, leading to less energy conversion from the climatological-mean flow to the monthly anomalies over the North Atlantic than the North Pacific (Simmons et al. 1983; Nakamura et al. 1987). The evaluation of the energetics based on the negative WH pattern shows a similar result, but with higher efficiency on the barotropic conversion from climatological-mean flows (CK) and the barotropic feedback from transient eddies (CK_{HF}).

5. Summary and discussion

In this work, we select monthly WH events when the WH pattern is dominant in the 500-hPa monthly geopotential height anomalies, and evaluate the observed features and energetics of the WH pattern based on these positive and negative WH events.

Although the WH pattern is identified by the nonlinear cluster analysis method, we can obtain the circulation signals resembling the WH pattern by the REOF analysis (6.75% of variance explained). It suggests that the WH pattern is a dominant low-frequency mode whatever the choice of the analysis method. The composite height anomalies at different levels show that the trough over the North Atlantic shifts slightly southward and westward from 850 to 500 hPa, while the height anomalies of the WH pattern show an equivalent barotropic structure in the upper troposphere.

The results of the energetics analysis associated with the WH pattern indicate that the baroclinic conversion from the climatological-mean flow is important and can maintain the temperature anomalies associated with the WH pattern, due to the strong horizontal shear of the climatological-mean temperature and the relevant heat flux to relax the background thermal gradient. Since the basic temperature contrasts between the colder continent and the warmer ocean is similar over the North Pacific and the North Atlantic, the result of CP over the North Atlantic associated with the WH pattern is consistent with that of the WP pattern over the North Pacific (Tanaka et al. 2016). However, the barotropic conversion CK is smaller in the WH pattern than that in the WP pattern, due to the differences between the structure and strength of the North Pacific jet and the North Atlantic jet. During positive WH events, the barotropic feedback of transient eddies contributes positively to

enhance the westerlies over the North Atlantic and maintain the WH pattern. It is in accordance with the result of Tan et al. (2017). The baroclinic feedback associated with eddy heat flux contributes negatively to the total energy, consistent with previous works (Lau and Nath 1991; Tanaka et al. 2016), and prevents the maintenance of the WH pattern in the middle and lower troposphere.

Tan et al. (2017) emphasized the importance of synoptic waves, including the downstream development of transient eddies, to the formation and maintenance of the WH pattern during the persistent WH events. In this work, the barotropic feedback of transient eddies is mainly significant over the North Atlantic in the upper troposphere. Owing to relatively low static stability (smaller σ) and the significant gradient on the climatological-mean temperature, the baroclinic conversion CP can mainly maintain the dipole temperature anomalies associated with the WH pattern in the middle and lower troposphere. Considering the efficiency of each energy conversion term, the baroclinic conversion from basic state and the barotropic feedback forcing from eddies are the two dominant processes to help maintain the WH pattern with the first and second highest efficiency, respectively.

WG81 identified five teleconnection patterns on the DJF 500-hPa height field in a dataset over a 15-yr period. Among these modes, the western Atlantic (WA) pattern resembles the WH pattern to some extent. We apply the REOF analysis on the monthly DJF Z500 anomalies during the same 15-yr period (from 1962/63 through 1976/77). The corresponding REOFs are shown in Fig. 8. The modes resembling the PNA and WP patterns are found in REOFs 1 and 5, respectively (Figs. 8a,b). The REOF 7 during the 15-yr period (Fig. 8d) resembling the WH pattern and the REOF 7 during the 60-yr period (Fig. 2d), with obvious positive anomalies over the Gulf of Alaska that does not emerge in the WA pattern (Fig. 20 in WG81), replaces the WA pattern. It suggests that the WA pattern appeared as partial signals of the WH pattern and was dominant during this specific 15-yr period. It is worth noting that the NAO mode does not appear while the eastern Atlantic (EA) pattern is prominent in the analysis of WG81 on the 500-hPa level. The REOF 6 (Fig. 8c) resembles the NAO pattern with the active center shifting eastward. It indicates that the NAO pattern moves eastward and resembles the EA pattern during winters from 1962/63 through 1976/77.

Mo and Livezey (1986) first identified the tropical–Northern Hemisphere (TNH) pattern by computing the correlation coefficients between height anomalies in the Northern Hemisphere and height anomalies at tropical

FIG. 8. Regressions of DJF monthly 500-hPa geopotential height anomalies on the standardized PCs of corresponding REOFs in a 15-yr period (from 1962/63 through 1976/77). The contour interval is 15 m in each frame; red (blue) contours denote positive (negative) values; the zero contours are omitted. Shading indicates statistical significance at the 95% level based on a two-sided t test. The title of each panel indicates the corresponding ranking, and the fractional variance is shown on the top-right side.

stations. They suggested that the TNH pattern is related to the tropical anomalies. Barnston and Livezey (1987) performed REOF analysis on 12 separate subsets of the 700-hPa height anomalies, each consisting of the monthly means for a single calendar month and obtained the TNH mode in the wintertime data (Fig. 5 in Barnston and Livezey 1987; <http://www.cpc.ncep.noaa.gov/data/teledoc/tnh.shtml>). It is obvious that the REOF 7 in Fig. 2d reflects the TNH pattern at the 500-hPa level. While it was not clear whether the variability of the TNH pattern identified from REOF analysis has correlations with sea surface temperature anomalies in the tropical Pacific, the naming for the TNH pattern was used following Mo and Livezey (1986).

The WH pattern resembles the TNH pattern to some extent. The positive phase of the TNH pattern features positive height anomalies over the Gulf of Alaska and from the Gulf of Mexico northeastward across the western North Atlantic, and negative height anomalies throughout eastern Canada. Comparing with the TNH pattern, the signals of the WH pattern extend eastward over the North Atlantic and westward over the Gulf of Alaska, leading to affect the atmospheric circulation in a wider range. In view of the high correlation between the WH index and the TNH index (Fig. 1b) and their resemblance, we think of the WH pattern and the TNH pattern as the same thing. Recent studies have suggested that a WH-like zonal dipole could be related to the

tropical west Pacific sea surface temperature anomalies, but not related to ENSO (Hartmann 2015). The anomalous tropical west Pacific warming was seen in a strong WH event during the 2013/14 winter (e.g., Lee et al. 2015; Seager and Henderson 2016). This seems not consistent with the associated tropical signals of the TNH pattern and its original definition (Mo and Livezey 1986). The correlation coefficients between the WH index and the 150-hPa divergence anomalies on monthly time scale are about 0.1 over the tropical west-central Pacific. They marginally reach statistical significance over small areas (not shown). The present study suggests that the WH pattern is an intrinsic dynamical mode with its maintenance through energetics from the climatological-mean state, however, for few cases, the WH pattern could be forced externally by tropical heating.

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