Modulations of Storm-Track Activity Associated with the Baroclinic Annular Mode

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ABSTRACT: The baroclinic annular mode (BAM) is the leading mode of variability in extratropical eddy activity characterized by its hemispheric-scale pulsing. Based on atmospheric reanalysis data for the Southern Hemisphere, this study reveals BAM-associated systematic modulations not only in fluxes associated with subweekly transient disturbances, as found by earlier studies, but also in their spatial structure involved in the dynamics of the BAM. Specifically, in the positive phase of the BAM characterized by enhanced activity of transient disturbances, their lower-tropospheric baroclinic structure becomes more distinct, and they tend to be more elongated meridionally in both the upper and lower troposphere. These BAM-associated structural modulations of the disturbances favor the more efficient baroclinic development via enhanced poleward heat transport and their downstream development, which can contribute to hemispheric-scale enhancement of kinetic energy associated with the disturbances. In addition, a tendency of the disturbances to exhibit horizontally tilting structure becomes more evident in the positive phase of the BAM, which is favorable for enhanced transport of westerly momentum from the subtropics to the midlatitude polar-front jet, or equivalently enhanced wave-activity propagation from the midlatitude storm track into the subtropics. This modulation lags the peak of anomalous kinetic energy of the disturbances, thus acting to contribute to the decay of the BAM signature. A set of numerical simulations suggests that the BAM-associated pulsing in storm-track activity and structural modulations are manifestations of atmospheric internal dynamics, which can be significantly amplified in the presence of a midlatitude oceanic frontal zone through the formation of more organized and coherent baroclinic wave packets.

KEYWORDS: Atmospheric circulation; Storm tracks; Intraseasonal variability; Atmosphere-ocean interaction; Annular mode

1. Introduction

Eastward-moving synoptic-scale cyclones and anticyclones give rise to day-to-day variations in local weather conditions in the midlatitudes, including precipitation, cloudiness, humidity, winds, and air temperature, and those transient disturbances are therefore quite important for the society. Furthermore, those disturbances are of a particular importance in the extratropical climate system through their systematic meridional transport of heat, momentum, and moisture. These disturbances are particularly active within zonally elongated “storm tracks” that typically form over the midlatitude oceans, in particular over major oceanic frontal zones where high near-surface baroclinicity is effectively maintained with sharp gradients of sea surface temperature (SST) (Nakamura et al. 2004).

The activity of transient disturbances, or storm-track activity, fluctuates on various temporal and spatial scales, causing weather extremes and climate variability. Recently, Thompson and Woodworth (2014) revealed that the leading mode of variability in eddy kinetic energy (EKE) in the extratropical Southern Hemisphere (SH) exhibits the zonally symmetric structure representing its pulsing, namely, the baroclinic annular mode (BAM). They pointed out that the BAM accounts for a large fraction of the variance in EKE and meridional eddy heat flux and precipitation (Thompson and Barnes 2014) and cloud radiative effects (Li and Thompson 2016). The characteristics of the BAM differ substantially from those of the Southern Annular Mode (SAM; Thompson and Wallace 1998, 2000), which is another major annular variability in the SH representing the north–south wobbling of the eddy-
driven polar-front jet (PFJ). For example, the SAM accounts for a larger fraction of the variance of meridional eddy momentum flux and zonal wind, and its variability is characterized by red spectrum with an e-folding time scale of ~10 days (Thompson and Woodworth 2014). The SAM is also associated with anomalous cloud radiative forcing (Wall et al. 2022), whose spatial structure differs substantially from that associated with the BAM (Li and Thompson 2016). The BAM signature can also be seen in the Northern Hemisphere (Thompson and Li 2015), despite interhemispheric differences in the topography.

For the mechanism of the BAM, some studies suggested the relevance of the dynamics of synoptic-scale baroclinic disturbances. Time evolution of the BAM can be interpreted within the framework of the energy cycle of baroclinic disturbances, where anomalous meridional heat and momentum fluxes are typical for the onset and decay stages of the BAM, respectively (Thompson and Woodworth 2014). These processes can be significantly amplified in the presence of a midlatitude oceanic frontal zone (Nakayama et al. 2021), which recurrently energizes baroclinic disturbances aloft (Nakamura et al. 2004, 2008). In an idealized model, Thompson and Barnes (2014) found that the quasi-periodic behavior of the BAM variability is consistent with baroclinic processes that contain a negative feedback between extratropical baroclinicity, poleward eddy heat flux, and radiative damping. More recent studies argued that the quasi-periodic behavior of the BAM variability can arise from baroclinic interactions via poleward eddy heat flux between upper-level wave packets propagating fast with eastward group velocity and low-level baroclinicity propagating eastward more slowly (Thompson et al. 2017) or geographically fixed over the south Indian Ocean (Xue et al. 2021). From another perspective, Wang and Nakamura (2016) hypothesized that interference between two wave components with different frequencies can yield the periodicity of the BAM. Their study highlighted the importance of propagating disturbances, although the physical mechanism for generating these two wave components remains to be clarified.

Many of the previous studies of the BAM analyzed eddies that are defined as local departures from the zonal-mean state. We note that those eddies consist of not only synoptic-scale baroclinic disturbances but also low-frequency quasi-stationary anomalies. Since those types of disturbances/anomalies are governed by different dynamics, this definition might yield potential difficulties in interpreting the underlying dynamics of the BAM. Given the importance of the dynamics of baroclinic disturbances on the BAM, this study investigates BAM-associated systematic modulations in the activity and structure of sub-weekly transient disturbances, which largely corresponds to migratory synoptic-scale systems (e.g., Blackmon et al. 1977).

This paper is structured as follows. Section 2 describes the data and analysis methods. Section 3 briefly reviews the characteristics of the BAM, including its spatial structure and time evolution. Section 4 investigates the structural modulations of transient disturbances and discusses their importance in the BAM dynamics. By analyzing output data from the same aquaplanet experiments as used in Nakayama et al. (2021), section 5 discusses the impacts of a midlatitude oceanic frontal zone on structure of transient disturbances and its BAM-associated modulations. Section 6 provides a summary and further discussions.

2. Data and methods

This study analyzes daily-averaged statistics derived from the Japanese 55-year reanalysis data (JRA-55; Kobayashi et al. 2015) produced by the Japan Meteorological Agency, in which 6-hourly data are available on a 1.25° × 1.25° grid system. In analyzing outgoing longwave radiation (OLR), we utilize the National Oceanic and Atmospheric Administration (NOAA) interpolated OLR data with a horizontal resolution of 2.5° × 2.5° based on satellite observations (Liebmann and Smith 1996). The results shown below are based on the data over 41 years from 1979 to 2019. Data for all calendar months are used for most of the analysis below.

In this study, sub-weekly fluctuations of a given variable associated with migratory transient disturbances (denoted below with primes) have been extracted through high-pass filtering with 8-day cutoff Lanczos filter. At each grid point, the activity of transient disturbances is assessed, for example, as kinetic energy associated with transient disturbances (TKE) as well as poleward heat and westerly momentum fluxes in the SH and upward heat flux defined as (u′u′ + v′v′)/2, −v′T′, −u′v′, and −ω′T′, respectively, where u denotes zonal wind velocity, v denotes the meridional wind velocity (multiplied by −1 to represent poleward motion with positive −v), ω denotes the pressure velocity (multiplied by −1 to represent upward motion with positive −ω), and T denotes the temperature. These quantities have been evaluated for every 6-hourly time step and then averaged for each of the days. Low-frequency variability of a given variable, including the activity of transient disturbances, has been extracted through low-pass filtering with 8-day cutoff Lanczos filter. Climatological means of the individual variables have been calculated by first applying 31-day running mean and then averaging for each calendar day over 41 years. Anomalies of a given variable are defined as deviations from its climatological mean.

As in Nakayama et al. (2021), the BAM has been extracted as the leading empirical orthogonal function (EOF) of low-frequency anomalies of [TKE], where square brackets denote zonal averaging. The EOF analysis was applied to [TKE] anomalies on a meridional plane defined as 20°–70°S and 925–200 hPa. Prior to the EOF analysis, [TKE] anomalies were weighted with both the square root of the cosine of latitude and the mass represented by each pressure level. The normalized principal component (PC) time series for the leading EOF is hereinafter referred to as a “BAM index.” By definition, its positive values correspond to positive [TKE] anomalies.

3. Structure and time evolution of the BAM anomaly

In this section, the typical spatial structure and time evolution of the BAM identified through the EOF analysis are briefly discussed. The corresponding discussions were also
made in more detail by Nakayama et al. (2021). Shading in Fig. 1a shows a meridional distribution of [TKE] anomalies typical for the positive phase of the BAM calculated by linearly regressing the anomalies onto the normalized BAM index. The first EOF (i.e., the BAM) is so dominant that it explains 58.3% of the total variance of [TKE] anomalies, which is statistically separated from the second EOF (19.5%) according to the criterion by North et al. (1982). The anomalous [TKE] is characterized by a broad monopole that largely overlaps with the corresponding climatological-mean [TKE] (contours in Fig. 1a). The BAM thus represents the pulsing of storm-track activity, consistent with previous studies (e.g., Thompson and Woodworth 2014). Its unit standard deviation corresponds to 20%–25% pulsing of [TKE] from its climatological mean, in agreement with Nakayama et al. (2021).

As pointed out by Thompson and Woodworth (2014), the BAM is characterized by a high degree of zonal uniformity. As evident in Fig. 1b, the 300-hPa TKE anomalies regressed onto the BAM index are positive everywhere in the extratropical SH. In fact, the PC time series corresponding to the first EOF of zonally varying 300-hPa TKE anomalies over the extratropical SH (20°–70°S) is highly correlated (r = +0.94) with the BAM index. Still, the BAM anomalies shown in Fig. 1b include some zonal asymmetries in their amplitude and peak latitude, reflecting those in the climatological-mean TKE. For example, particularly high TKE in both climatology and its BAM-associated anomalies over the south Indian Ocean are attributable at least in part to the underlying pronounced oceanic frontal zone along the Agulhas Return Current (Nakamura et al. 2008; Nakayama et al. 2021).

Typical time evolutions of the BAM anomalies are summarized in Fig. 2, which shows lag-regression anomalies of several variables onto the BAM index featuring its positive phase. By definition, the upper-tropospheric [TKE] anomaly maximizes simultaneously with the BAM index (Fig. 2f). The peak times of the [−u′ T′] and [−ω′ T′] anomalies precede the peak of the BAM index by ~1 day (Figs. 2a,b). This is consistent with the generation of anomalous [TKE] by anomalous baroclinic development of transient disturbances, where zonal-mean available potential energy (APE) is converted into APE associated with transient disturbances (TAPE) and then to TKE (Thompson and Woodworth 2014; Nakayama et al. 2021). The strengthening (weakening) of near-surface meridional temperature gradient [θ T/θy] (i.e., baroclinicity) along the storm track precedes (lags behind) the peak of the positive [−u′ T′] anomalies (Figs. 2a,c). This is consistent with the two-way feedbacks between poleward eddy heat flux and baroclinicity suggested by Thompson and Barnes (2014). The anomalous precipitation (Fig. 2d) can also contribute to the generation of anomalous [TAPE]. which is accompanied by anomalous [−ω′ T′] (i.e., conversion from [TAPE] to [TKE]; Fig. 2b). The positive (negative) precipitation anomaly also tends to be accompanied by a negative (positive) [OLR] anomaly (Fig. 2e), which corresponds to the enhanced (reduced) convective activity. The peak times of the [−u′ T′] anomalies lag behind the [TKE] peak by ~1 day and 1–3 days, respectively (Figs. 2h–j), which is consistent with the energy conversion from TKE to zonal-mean KE for the decay of TKE. As presented in Nakayama et al. (2021), the BAM-associated [u] anomaly represents a meridional shift of the PFJ (Figs. 2i,j) with a certain projection on the SAM-associated [ω] anomaly. The entire evolution of the BAM signature can be thus interpreted from a viewpoint of a typical life cycle of baroclinic disturbances.

Negative anomalies in [TKE], [−u′ T′] and precipitation and positive [OLR] anomalies after the peak of the positive BAM (Figs. 2a,d–f) may be related to the enhancement of equatorward wave propagation (i.e., positive [−u′ u′′] anomalies) and reduced downstream propagation of wave packets (Thompson et al. 2017; Boljka et al. 2021). It is noteworthy that the significant negative precipitation anomalies and positive [OLR] anomalies both start emerging on the equatorward side of the enhanced storm-track activity as early as 2 days after its peak time, followed by the reduction of [−ω′ T′]. Meanwhile, the positive precipitation anomalies spread poleward as the enhanced storm-track activity peaks, and they remain for the next few days along the intensified westerlies at subpolar latitude. This suggests the importance of moisture processes for the phase transitions of the BAM, though this should be verified, for example, through comparison with dry simulations as performed by Lutsko and Hell (2021) for the SAM.

Regarding the relationship between the BAM and SAM, Thompson and Woodworth (2014), who analyzed the BAM
FIG. 2. Lag-latitude sections of anomalous (a) 850-hPa \(-\nu^'T^'\), (b) 500-hPa \(-\omega^'T^'\), (c) 850-hPa \(\partial T/\partial y\), (d) [precipitation], (e) [OLR], (f) 300-hPa [TKE], (g) 300-hPa \([W_s(x)]\), (h) 300-hPa \(-u'u'\), (i) 300-hPa \([u]\), and (j) 850-hPa \([u]\). Each panel represents typical evolution of anomalies of a particular variable during the positive phase of the BAM obtained as linear regression against the BAM index with a given lag. Positive lags represent anomalies lagging behind the BAM index. Contours are drawn for \(60.2, 60.6, \ldots\) (K m s\(^{-1}\)) in (a), \(60.003, 60.009, \ldots\) (Pa s\(^{-1}\)) in (b), \(60.005, 60.015, \ldots\) (K 100 km\(^{-1}\)) in (c), \(60.02, 60.06, \ldots\) (mm day\(^{-1}\)) in (d), \(60.075, 60.225, \ldots\) (W m\(^{-2}\)) in (e), \(63, 69, \ldots\) (m\(^2\) s\(^{-1}\)) in (f), \(62, 66, \ldots\) (m\(^2\) s\(^{-1}\)) in (g), \(61, 63, \ldots\) (m\(^2\) s\(^{-1}\)) in (h), \(60.2, 60.6, \ldots\) (m s\(^{-1}\)) in (i), and \(60.1, 60.3, \ldots\) (m s\(^{-1}\)) in (j). Dashed lines for negative anomalies. \([\nu^'T^']\) and \([u'u']\) are multiplied by \(-1\) so that their positive values correspond to poleward heat and westerly momentum fluxes, respectively, in the SH. In addition, \([\omega^'T^']\) is also multiplied by \(-1\) so that its positive value represents upward heat flux. Red (blue) shading shows the 95% confidence level of the corresponding positive (negative) correlations based on a one-sided \(t\) test. The effective degree of freedom of the analysis is estimated as \(N_e = N(1 - r_{BAM}r_{anom})(1 + r_{BAM}r_{anom})\), where \(N\) denotes the number of days to be analyzed, and \(r_{BAM}\) and \(r_{anom}\) denote 1-day autocorrelations of the BAM index and each of the anomalies, respectively.
based on eddies defined as local departure from the zonal mean state, pointed out that the two modes are temporally independent from one another \((r \sim 0.09\) when the SAM index lags behind the BAM index by 1 day based on our analysis of the JRA-55). Meanwhile, this study and Nakayama et al. (2021), who analyzed the BAM based on subweekly transient disturbances, found a weak but significant correlation between them \((r \sim 0.18\) when the SAM index lags behind the BAM index by 2–3 days), although the BAM accounts only for less than 5% of the variance of the SAM. This discrepancy is probably because subweekly transient disturbances and low-frequency quasi-stationary disturbances might yield \(u\) anomalies in a different manner as noted by Hoskins et al. (1983) in association with their pulsing, which should be clarified in a future study.

The BAM accompanies not only the modulated wave-activity translation in the meridional plane related to heat and momentum fluxes associated with transient disturbances but also the modulated wave-activity propagation in the zonal direction. The latter can be evaluated with a wave-activity flux formulated by Takaya and Nakamura (2001). The flux \(\mathbf{W}\) consists of two terms as

\[
\mathbf{W} = \mathbf{W}_{s} + C_{u} M,
\]

where \(M\) denotes the wave-activity pseudomomentum, \(C_{u}\) the local phase speed of waves in the direction of the time-mean flow. Under the Wentzel–Kramers–Brillouin approximation, the flux \(\mathbf{W}\) is parallel to the local velocity vector of stationary Rossby wave without any dependency on wave phase in theory. Since \(C_{u} M\) represents the propagation of wave packets with their phase speed \((C_{u})\), the “stationary component” \(\mathbf{W}_{s}\) represents their propagation relative to the phase propagation. Therefore, the downstream development of eastward-moving synoptic-scale disturbances (e.g., Chang 1993) can be represented by the eastward \(\mathbf{W}_{s} [W_{s}(x)]\) in the spherical coordinate \(W_{s}(x)\) may be written as

\[
W_{s}(x) = \frac{1}{2|\bar{U}|} \left[ \frac{C_{u}^{2} \bar{U}^{2}}{a^{2} \cos \phi} \frac{\partial \Phi^{2}}{\partial \lambda} - \frac{\bar{U}}{a^{2}} \frac{\partial^{2} \Phi^{2}}{\partial \lambda^{2}} + \frac{V}{a^{2}} \frac{\partial \Phi^{2}}{\partial \phi} \frac{\partial^{2} \Phi^{2}}{\partial \lambda^{2} \partial \phi} \right],
\]

where \(\Phi = \Phi/g\) denotes geostrophic streamfunction \([\Phi\) is geopotential and \(g = 9.8 \text{ m s}^{-2}\) gravitational acceleration], \(\bar{U} = (U, V)\) climatological-mean horizontal wind vector as the basic state, \(\lambda\) longitude, \(\phi\) latitude, and \(a = 6.37 \times 10^{6} \text{ m}\) the radius of Earth.

Figure 3 shows meridional profiles of various statistics related to background flow and transient disturbances, including upper-tropospheric \([W_{s}(x)]\) (Fig. 3i), composited separately for the positive and negative phases of the BAM, which are defined as the days when the BAM index is greater than +1 and less than −1, respectively. The number of days in the positive (negative) phase of the BAM based on above threshold is

\[1\text{ We may alternatively use 8-day low-pass-filtered horizontal wind vector as a basic state, which leads to no substantial discrepancy of the results (see Fig. S1 in the online supplemental material).} \]
2333 (2402) out of the 14975 days in total. When zonally averaged, upper-tropospheric \( W_s(x) \) is still positive throughout the midlatitudes (Fig. 3i), which indicates the distinct downstream development of transient disturbances (Lee and Held 1993). The \( W_s(x) \) markedly increases in the positive phase of the BAM relative to its negative phase, suggesting the enhancement of downstream development. Anomalous \( W_s(x) \) precedes the BAM index by \( 0.5 \) days (Fig. 2g). Since the downstream development can extend transient disturbances into broader areas (e.g., Chang 1993) for subsequent baroclinic development, this anomalous \( W_s(x) \) can be another important factor that can contribute to the hemispheric-scale amplification of the BAM signature (Thompson et al. 2017; Xue et al. 2021).

4. Systematic structural modulations of transient disturbances associated with the BAM

In this section we demonstrate that the BAM-associated anomalies shown in the preceding section are associated with significant modulations of their spatial structure. Specifically, the BAM-associated modulations of lower-tropospheric \( [-\nu'/T'] \) (Fig. 2a) are related to the modulated baroclinic structure of transient disturbances. Figure 4 shows the one-point regression maps of \( -\nu'/T' \) at 850 hPa based on a normalized time series of 850-hPa \( T' \) at grid points in the vicinity of the PFJ axis (denoted with crosses) over the (left) south Indian Ocean; (center) South Pacific; and (right) South Atlantic. The regressions are based on the data sampled separately for the positive and negative phases of the BAM in which the BAM index exceeds its unit standard deviations in magnitude.

Fig. 4. Maps of one-point regressions of 850-hPa \( T' \) (shading; color bar below) and \( -\nu' \) (contour for \( \pm 0.4, \pm 1.2, \pm 2.0, \ldots \) m s\(^{-1}\), dashed for equatorward winds) for the (a),(c),(e) positive and (b),(d),(f) negative phases of the BAM. Reference for the one-point regression is the normalized time series of 850-hPa \( T' \) at grid points in the vicinity of the PFJ axis (denoted with crosses) over the (left) south Indian Ocean; (center) South Pacific; and (right) South Atlantic. The regressions are based on the data sampled separately for the positive and negative phases of the BAM in which the BAM index exceeds its unit standard deviations in magnitude.
systematically larger absolute values than in the negative phase over each of the ocean basins. This is quantified for each phase and basin with the averaged values of the two maximum negative correlations of $T'$ and $-\nu'$ to the east and west of the reference grid points (values near the upper-right corners of each panel). All the differences in the maximum negative correlations between the two phases of the BAM are found to be statistically significant at the 95% confidence level. The locations of local maxima and minima of one-point correlations of $T'$ and $-\nu'$ are almost identical between the two phases, indicative of no systematic changes in typical zonal wavelength of wavy disturbances. Furthermore, spatial overlapping between $T'$ and $-\nu'$ as inferred from the correlation maps also shows no apparent changes. Nevertheless, in the positive phase of the BAM, the correlations are systematically higher, which is consistent with systematically higher positive correlation downstream and thus suggestive of the more available potential energy would be converted from the mean zonal flow to disturbances, which is favorable for the subsequent increase of [TKE]. In this sense, the cor.$[-\nu', T']$ may be equivalent to the “eddy efficiency” for the APE conversion from the zonal-mean flow to eddies as formulated by Schemm and Rivière (2019), who evaluated its change associated with the midwinter suppression of storm-track activity over North Pacific (Nakamura 1992). Okajima et al. (2022) also examined cor.$[\nu', T']$ in study of the midwinter suppression.

In Fig. 3c, latitudinal distributions of cor.$[-\nu', T']$ at 850 hPa are compared between the positive and negative phases of the BAM. Positive cor.$[-\nu', T']$ exceeds +0.5 in midlatitudes where lower-tropospheric [$\bar{T}$]$\bar{\nu}$ is relatively large (Fig. 3a), confirming baroclinic structure of transient disturbances along a midlatitude baroclinic zone. This is the case for both the positive and negative phases of the BAM, although the correlation is systematically higher in the positive phase. The difference in the correlation between the two phases is statistically significant primarily along the storm track and its equatorward flank. In fact, in the positive phase of the BAM, the highest cor.$[-\nu', T']$ exceeds +0.6 around 40°–45°S (Fig. 3c).
on the equatorward flank of the storm track (Fig. 3b), in contrast to the negative phase where the maximum cor. $-\nu'$ to $T'$ slightly above +0.5 is observed around the storm-track axis. A possible factor may be the effect of moisture. Specifically, in the positive phase of the BAM, condensation heating associated with precipitation is enhanced especially on the equatorward flank of the storm track before the peak time of $[TKE]$ (Fig. 2d). This moisture effect may contribute to the baroclinic development of transient disturbances, although verification of this hypothesis should be made in future studies.

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Fig. 6. As in Fig. 4, but for one-point correlations of 850-hPa $T'$ (shading) and $-\nu'$ (contour for $0.1$, $0.2$, $0.3$, $0.4$, and $0.6$) for the (a),(c),(e) positive and (b),(d),(f) negative phases of the BAM. The averages of the maximum negative correlations of $T'$ to the east and west of the reference grid points are denoted near the upper-right corner of each panel. (g)–(l) As in (a)–(f), respectively, but for one-point correlation of 300-hPa $z'$. Reference for one-point correlation is the time series of 300-hPa $z'$. Contours of (g)–(l) show the composited 300-hPa $u$ for the corresponding phases. The averages of maximum negative correlations of $z'$ to the east and west of the reference points are denoted near the upper-right corner of each panel.
Furthermore, it may be related to the stronger tendency of transient disturbances to exhibit meridional elongation in the positive phase of the BAM (Fig. 6). The higher cor.$\left[\nu', T'\right]$ in the positive phase of the BAM is consistent with the systematically larger absolute values of the one-point correlation (Figs. 6a–f).

The BAM-associated modulations in cor.$\left[\nu', T'\right]$ can be linked to the $\left[\nu'T'\right]$ anomalies preceding the peak of the BAM signature. Figures 7a and 7b show the typical time evolutions of lower-tropospheric cor.$\left[\nu', T'\right]$ and $\left[\nu'T'\right]$ composited for the positive and negative BAM events, respectively. The reference days for positive (negative) BAM events are defined as the days when the normalized BAM index reaches its local maxima larger than +1 and its local minima smaller than −1, respectively. Dashed lines are for negative values.

**Fig. 7.** Lag–latitude sections of (a),(b) cor.$\left[\nu', T'\right]$ (shading) and $\left[\nu'T'\right]$ (contour, K m s$^{-1}$) at 850 hPa; (c),(d) cor.$\left[u', \nu'\right]$ (shading) and $\left[-u'\nu'\right]$ (contour, m$^2$ s$^{-2}$) at 300 hPa; and (e),(f) $\sigma(\nu')/\sigma(u')$ (shading) and a zonal component of the stationary component of the wave–activity flux $W_s(x)$ formulated by Takaya and Nakamura (2001) (contour; m$^2$ s$^{-2}$) at 300 hPa, all composited for (left) positive and (right) negative BAM events that are defined as the days when the normalized BAM index reaches its local maxima larger than +1 and its local minima smaller than −1, respectively. Dashed lines are for negative values.
positive phase, cor.$[-u', \ T]$ minimizes $\sim$1 day before the negative peak of the BAM index (Fig. 7b).

These results indicate that, in the positive (negative) phase of the BAM, baroclinic structure of transient disturbances tends to be more (less) pronounced, favorable for more active (inactive) baroclinic growth and thus the subsequent increase (decrease) in [TKE]. In fact, the red dotted line in Fig. 3b shows a hypothetical $[-u' T]$ calculated at each altitude as a product of eddy amplitude term $([u' v'] [T' T])$ composited for the positive phase and cor.$[-u', \ T]$ composited for the negative phase. The difference between red dotted and blue solid lines thus indicates the hypothetical BAM-associated modulations in $[-u' T]$ that would be realized without any modulations in cor.$[-u', \ T]$ or structure of disturbances. Unlike in observations, the BAM-associated modulation in $[-u' T]$ averaged between 40° and 60°S would be reduced by $\sim$30% without any modulation in cor.$[-u', \ T]$, suggestive of the importance of the BAM-associated modulations in baroclinic structure of transient disturbances.

Meanwhile, cor.$[-u', \ T]=[-u' T] \sqrt{[u' v'] [T' T]}$ is related to the conversion of [TAPE] into [TKE] for transient disturbances. The correlation is almost the same between the two BAM phases (Fig. 3c), while $[-u' T]$ is significantly larger in the positive phase (Fig. 3d). Therefore, the $[-u' T]$ anomaly shown in Fig. 2b is attributed mostly to the amplitude modulations (i.e., pulsing) of transient disturbances. It is noteworthy that cor.$[-u', \ T]$ maximizes at subpolar latitudes in both phases, which may be related to poleward evolution of the BAM-associated anomalies in $[-u' T]$ and precipitation (Figs. 2b, d).

The meridional momentum flux $[-u' v']$ can be linked to the horizontally tilted structure of transient disturbances. Figures 6g-l show one-point correlation maps of 300-hPa $z'$ based on the local time series of $z'$ in the same manner as in Figs. 6a-f. Contours represent the 300-hPa $u$ composited separately for the two phases (but not anomalies). In the positive phase of the BAM, the PFJ exhibits a slight but significant poleward shift (Figs. 3f and 6g-l; Nakayama et al. 2021), which mainly reflects the signatures observed over the South Atlantic and Indian Ocean. For both phases of the BAM, the correlation patterns indicate a tendency for disturbances to exhibit a northwest–southeast axial tilt on the equatorward flank of the PFJ, especially over the South Atlantic and Indian Ocean. Over the South Pacific, by contrast, the positive phase of the BAM is characterized by stronger PFJ and weaker subtropical jet (Fig. 6i), especially in austral winter, and vice versa in the negative phase (Fig. 6j).

This tendency in the horizontally tilted structure of the disturbances can be verified statistically in Fig. 3h, which shows the correlation between $u'$ and $-v'$ calculated as cor.$[u', \ -v']=[-u' v'] \sqrt{[u' v'] [v' v']}$. The upper-tropospheric cor.$[u', \ -v']$ is positive on the equatorward side of $\sim$55°S with its maximum around 30°–40°S (Fig. 3h). The positive cor.$[u', \ -v']$ indicates a tendency of high-pass-filtered height anomalies to exhibit an apparent northwest–southeast axial tilt (Figs. 6g-l) and thereby yield net transport of westerly momentum from the subtropics to the midlatitude PFJ around $\sim$50°S (Fig. 3f) as well as wave-activity propagation from the midlatitude storm track into the subpolar. From a perspective of energetics, the positive cor.$[u', \ -v']$ on the equatorward flank of the PFJ can be interpreted as a tendency for transient disturbances to exhibit structure that gives rise to their decay through barotropic energy conversion, i.e., giving up their kinetic energy to that associated with $\omega$. The higher cor.$[u', \ -v']$ therefore corresponds to the more efficient barotropic decay of the disturbances. As shown in Figs. 3g and 3h, cor.$[u', \ -v']$ maximizes on the equatorward side of the $[-u' v']$ maximum. Positive cor.$[u', \ -v']$ is evident from midlatitudes into the subtropics, reflecting the northwest–southwest tilt of the disturbances (Figs. 6g-l). Nevertheless, $[-u' v']$ itself maximizes on the equatorward flank of the PFJ in the vicinity of the storm-track axis, where wind fluctuations and therefore $[u' u']$ and $[v' v']$ are much stronger.

The BAM-associated modulations in this tilting structure of transient disturbances are found to be linked to the $[-u' v']$ anomaly. Compared to the negative phase of the BAM, upper-tropospheric cor.$[u', \ -v']$ is higher in its positive phase in the subtropics and midlatitudes (Fig. 3h), which is consistent with systematically larger absolute values in the one-point correlation maps (Figs. 6g-l). Significant differences in cor.$[u', \ -v']$ between the two phases are found around 35°–40°S. The red dotted line in Fig. 3g shows a hypothetical $[-u' v']$ profile as a product of eddy amplitude term $([u' v'][v' v'])$ composited for the positive phase and cor.$[u', \ -v']$ composited for the negative phase, as done for $[-u' T]$ (Fig. 3b). If measured by $[-u' v']$ averaged between 30° and 50°S on the equatorward flank of the PFJ, the BAM-associated modulations in $[-u' v']$ would be reduced substantially by as much as 55%–60% without any structural modulations of disturbances as represented in cor.$[u', \ -v']$. The latitude of the zero cor.$[u', \ -v']$ is located slightly poleward in the positive phase of the BAM than in its negative phase (Fig. 3h), in agreement with the slight poleward shift of the eddy-driven PFJ (Fig. 3f; Nakayama et al. 2021).

Figures 7c and 7d show typical evolutions of upper-tropospheric cor.$[u', \ -v']$ and $[-u' v']$ composited for the positive and negative BAM events, respectively, in the same manner as in Figs. 7a and 7b. On the equatorward flank of the PFJ, the positive cor.$[u', \ -v']$ maximizes (minimizes) $\sim$1 day after the peak of the positive (negative) BAM events, which is favorable for the increase (decrease) of $[-u' v']$. These results suggest that, in the positive (negative) events of the BAM, the westerly momentum flux by transient disturbances from the subtropics to the midlatitude PFJ increases (decreases) due not only to amplified (weakened) transient disturbances but also to their modulated structure with tendency of more (less) apparent northwest–southeast axial tilt of high-pass-filtered height anomalies associated with transient disturbances (Figs. 3h and 6g-l). This structural modulation is favorable for more (less) effective [TKE] decay through barotropic energy conversion into the PFJ after the peak of positive (negative) BAM events.

Furthermore, the BAM-associated anomalies of $[W_{ao}]$ (Figs. 2f and 3i) are found to be related not only to the pulsing of storm-track activity but also to the modulated deformation of disturbances related to their meridionally elongated structure (see appendix A). Figure 3j compares the composited
\[ [\sigma'(u')/\sigma(u')] = \sqrt{[u' u'']/[u' u']} \] between the positive and negative phases of the BAM. Its value greater than 1 corresponds to meridionally elongated structures of transient disturbances. Since \( u' u' - u'' u' \) is related to the eastward component of the extended Eliassen–Palm (EP) flux (Hoskins et al. 1983) and wave-activity flux (Takaya and Nakamura 2001), meridionally elongated disturbances are favorable for efficient downstream development. Regardless of the phase of the BAM, the ratio \( [\sigma'(u')/\sigma(u')] \) significantly exceeds 1 (Fig. 3), as a manifestation of typical meridionally elongated structure of subweekly transient disturbances (e.g., Blackmon et al. 1977). The ratio is higher in the positive phase than in the negative phase (Fig. 3), representing enhanced meridional elongation of the disturbances in the positive phase. This tendency is in agreement with what is observed in the one-point correlation maps of upper-tropospheric \( z' \) (Figs. 6g–i), where the disturbances appear to be more anisotropic in the positive phase. The latitudinal maximum of \([W_{e(x)}]\) is slightly on the equatorward side of that of \([\sigma(u')/\sigma(u')]\) (Figs. 3d,f), partly because the downstream development is enhanced also along the wintertime subtropical jet with relatively low \([\sigma(u')/\sigma(u')]\).

Furthermore, Figs. 7e and 7f show the lag composites of \([W_{e(x)}]\) and \([\sigma(u')/\sigma(u')]\) for the positive and negative BAM events, respectively. The ratio \( [\sigma'(u')/\sigma(u')] \) maximizes (minimizes) before the peaks of the BAM events by ~1 day, consistent with the corresponding enhancement (reduction) of \([W_{e(x)}]\). The positive (negative) phase of the BAM is thus characterized by a stronger (weaker) tendency for transient disturbances to be meridionally elongated and thus more (less) favorable for their efficient downstream development. This can be a factor contributing to the development of the zonally uniform BAM signature, because the downstream development of upper-tropospheric disturbances can induce subsequent baroclinic development farther to the east.

5. Impacts of a midlatitude oceanic frontal zone assessed through aquaplanet experiments

Nakayama et al. (2021) showed significant impacts of a midlatitude oceanic frontal zone, characterized by pronounced meridional SST gradient, on the spatial structure and amplitude of the BAM signature. In this section, the corresponding influence on the typical structure of transient disturbances and its BAM-associated modulations is assessed by analyzing the output of the same aquaplanet experiments as used by Nakayama et al. (2021).

The aquaplanet experiments were conducted by Ogawa et al. (2012, 2016) with the AGCM for Earth Simulator (AFES; Ohfuchi et al. 2004; Enomoto et al. 2008; Kuwano-Yoshida et al. 2010) with a horizontal resolution of T79 (corresponding to ~150-km grid intervals) and 56 vertical levels up to 0.09 hPa. The lower-boundary condition is a fully global ocean with no landmass and sea ice. The prescribed SST profiles (Figs. 8a,b) are perpetual and zonally uniform. In a control (CTL) experiment, the climatological-mean meridional SST profiles over the south Indian Ocean (60°–80°E), characterized by a prominent oceanic frontal zone at 45° latitude, for austral summer (December–February; Fig. 8a) and winter (June–August) are prescribed to the model Northern and Southern Hemispheres, respectively. In the NF experiment, by contrast, SST on the poleward side of ~45° is raised to eliminate the oceanic frontal zones (Fig. 8b). The model was integrated for 120 months after a 6-month spinup under insolation fixed to the summer solstice condition for the model Northern Hemisphere. More detailed descriptions of the experiments are found in section 2 of Nakayama et al. (2021).

The model BAM is defined as the leading EOF of low-frequency variability in [TKE], as performed for the JRA-55 in section 2. As shown by Nakayama et al. (2021), the BAM extracted in the two experiments represents hemispheric-scale pulsing of TKE (their Fig. 3). The BAM in the CTL experiment well reproduces its observed counterpart with respect to its structure and amplitude, while amplitude of the BAM is substantially reduced in the NF experiment (Nakayama et al. 2021). Figure 8 shows the corresponding results in Fig. 3 for the model Northern (summer) Hemispheres of the CTL and NF experiments. For straightforward comparison with Fig. 3, the bottom side of each panel corresponds to higher latitudes, and the positive \([ -u'T ] \) and \([ -u''u' ] \) represent poleward heat and momentum fluxes, respectively. The CTL experiment is characterized by prominent lower-tropospheric \([pT/\sigma(u')] \) (Fig. 8c) associated with the oceanic frontal zone, along which the storm track and eddy-driven PFJ are anchored (Figs. 8e,i). In the NF experiment, by contrast, the storm-track activity is substantially reduced and displaced equatorward (Fig. 8f) with the equatorward-shifted PFJ (Fig. 8j) under the reduced \([pT/\sigma(u')] \) (Fig. 8d) with no distinct lower-tropospheric baroclinic zone in the absence of frontal SST gradient (Fig. 8b).

In both the CTL and NF experiments, BAM-associated structural modulations of transient disturbances are qualitatively consistent with their observational counterpart shown in the preceding section. In the positive phase of the BAM, 1) lower-tropospheric \([ -u'T ] \) in midlatitudes increases (Figs. 8e,f) and so does \(\text{cor.}[ -u', T ] \) (Figs. 8g,h); 2) upper-tropospheric \([ -u''u' ] \) (Figs. 8k,l) and \(\text{cor.}[ u', -u' ] \) (Figs. 8m,n) both increase between the subtropics and PFJ, and 3) so do upper-level \([W_{e(x)}] \) (Figs. 8o,p) and \([\sigma'(u')/\sigma(u')] \) (Figs. 8q,r) around the storm track. These results suggest that the BAM-associated modulations in storm-track activity would occur even if the underlying oceanic frontal zone were absent. These modulations are therefore considered as a manifestation of processes in atmospheric internal dynamics. Consistent results have been obtained for the model winter hemisphere.

Nevertheless, the oceanic frontal zone significantly amplifies not only the climatological-mean storm-track activity but also the BAM variability by efficiently restoring the meridional gradient of near-surface temperature (i.e., baroclinicity) and thereby supporting the recurrent development of transient disturbances (Nakayama et al. 2021). For example, in the NF experiment, lower-tropospheric \([ -u'T ] \) around the storm track is climatologically smaller in magnitude than in the CTL experiment, and its BAM-associated variability is also weaker (Figs. 8e,f). This indicates that an oceanic frontal zone significantly activates not only baroclinic development climatologically (e.g., Nakamura et al. 2008) but also its
BAM-associated modulations (Nakayama et al. 2021). Additionally, positive cor.\(\mathbf{y}'\mathbf{T}'\) is signifi-
cantly higher in the CTL experiment than in the NF experiment (Figs. 8g,h).

Around the upper-tropospheric storm track, not only \(W_s(x)\) but also \(s(x')/s(u')\) are systematically greater in the CTL experiment (Figs. 8o–r), and so are the case in the upper-tropospheric positive \([-u'v']\) and cor.\([u', -v']\) between the subtropics and PFJ (Figs. 8k–n). These results suggest that, in the presence of a midlatitude oceanic frontal zone, the BAM signatures, including its magnitude and associated structural modulations of transient disturbances, are simulated much more realistically as captured in the JRA-55 data than in the NF experiment with no oceanic frontal zone.

6. Discussion and conclusions

The BAM is the leading mode of variability in extratropical eddy activity, characterized by its hemispheric-scale pulsing (Thompson and Woodworth 2014). As an attempt to deepen our understanding of its dynamics, the present study has investigated BAM-associated systematic modulations in activity and structure of subweekly transient disturbances by using atmospheric reanalysis data. As pointed out by previous studies (Thompson and Woodworth 2014; Nakayama et al. 2021), the present study has confirmed that typical time evolution of the
BAM can be interpreted as that of baroclinic disturbances but modulated to yield anomalous heat and momentum fluxes coherently as manifested in zonal-mean eddy statistics. This study has also verified the BAM-associated pulsing of the downstream development of migratory transient disturbances by evaluating their eastward wave-activity flux, which has been regarded as an essential process to yield the BAM signature (Thompson et al. 2017; Xue et al. 2021).

Although the BAM-associated variations in the eddy fluxes have been considered to be yielded by the pulsing of storm-track activity itself, this study is the first to find that they are also linked to structural modulations of transient disturbances by assessing statistics that are independent of eddy amplitude. Specifically, this study has revealed that the BAM variability accompanies significant modulations of the baroclinic structure of subweekly migratory disturbances between its positive and negative phases. During the development stage of a positive BAM events, the baroclinic structure of those disturbances becomes more pronounced, exhibiting higher correlation between temperature and meridional wind fluctuations. Their baroclinic growth is therefore enhanced through the APE conversion from the background baroclinic westerlies via stronger poleward heat flux in the lower troposphere and through the energy conversion into TKE via stronger upward heat flux. These BAM-associated modulations in the baroclinic structure of transient disturbances seem relevant to the variability in poleward eddy heat flux in the two-way feedbacks between the heat flux and baroclinicity proposed by Thompson and Barnes (2014) to explain the BAM-associated periodicity. At the same time, the disturbances are more elongated meridionally, and therefore their increased wave activity via their enhanced baroclinic growth can be translated downstream more efficiently through enhanced downstream development, leading to the increase in [TKE].

During the decay stage of the positive BAM events, the enhanced meridional transport of westerly momentum by upper-tropospheric disturbances is relevant not only to the amplified storm-track activity but also to the stronger tendency for the disturbances to exhibit northwest–southeast axial tilting, leading to the enhanced decrease of [TKE] through the barotropic energy conversion into the time-mean westerlies. The opposites are true for the negative phase of the BAM. Although the analyses shown in Figs. 1–7 are based on data in all seasons, qualitatively consistent results are obtained for the analyses conducted separately for austral summer (December–February) and winter (June–August) (not shown).

As an extension of Nakayama et al. (2021), who suggested the BAM-associated modulations of meridional heat and momentum fluxes by transient disturbances, the new findings in this study have revealed an important role of the structural modulations of migratory transient disturbances in the BAM dynamics. Our additional investigation of the aquaplanet experiments analyzed by Nakayama et al. (2021) suggests that these modulations are a manifestation of atmospheric internal dynamics, but a midlatitude oceanic frontal zone is found to render transient disturbances more baroclinic and elongated meridionally to help amplify the BAM variability significantly. As shown in appendix B, the corresponding structural modulations are less significant for eddies that are defined as local departures from the zonal means and thus include quasi-stationary anomalies in addition to migratory transient eddies. Focusing only on migratory transient eddies has led to our findings of the BAM-associated structural modulations of migratory transient disturbances. We expect that this approach will be effective to analyze the BAM in the Northern Hemisphere (Thompson and Li 2015), where planetary-scale stationary waves have much larger amplitudes climatologically than in the SH. Still, further study is needed to investigate specific mechanisms that are responsible for those structural modulations as revealed in this study in the course of the BAM evolution.

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Data availability statement. The JRA-55 reanalysis dataset is available from the Japan Meteorological Agency on the website https://jra.kishou.go.jp/JRA-55/index_en.html, and has been provided by way of Meteorological Research Consortium. The NOAA Interpolated outgoing longwave radiation data are available from the NOAA Physical Sciences Laboratory on the website: https://psl.noaa.gov/data/gridded/data.olscdr.interp.html.

APPENDIX A

Physical Interpretation of Downstream Development of Meridionally Elongated Disturbances

In this appendix, we schematically explain why the downstream development would be stronger for more meridionally elongated disturbances, even if amplitude of their pressure anomalies were fixed. A similar discussion has been made in section 4 of Takaya and Nakamura (2001). As shown in a schematic (Fig. A1), we assume that a wave train of transient disturbances without any horizontal tilting is embedded in the horizontally uniform westerly basic flow ($U_x$; gray thick arrow) in the SH. The disturbances are traveling eastward in the upper troposphere with phase speed $c$ ($<U_x$). Black lines represent contours of streamfunction perturbations ($\psi'$).
A linearized meridional momentum equation on a β plane with a quasigeostrophic scaling may be written as

\[ \frac{\partial u'_y}{\partial t} + U_g \frac{\partial u'_y}{\partial x} + f_0 u'_a + \beta y u'_g = 0, \]

where subscripts “g” and “a” denote geostrophic and ageostrophic components, respectively, \( f = f_0 + \beta y \) denotes the Coriolis parameter, and capital letters and primes denote basic state and perturbations, respectively. From an observer moving eastward with \( c \), we may write the following:

\[ (U_g - c) \frac{\partial u'_y}{\partial x} + f_0 u'_a + \beta y u'_g = 0. \]

Then, at or around cyclonic or anticyclonic centers of the disturbances where \( u'_y \sim 0 \), an approximate balance is

\[ -(U_g - c) \frac{\partial u'_y}{\partial x} - f_0 u'_a, \]

in order for the disturbances to propagate with a given phase speed \( c < U_g \).

In Fig. A1, the eastward advection of anomalous meridional wind momentum \( -(U_g - c)\partial u'_y/\partial x \) acts to generate northward and southward accelerations around the cyclonic and anticyclonic centers of \( \psi' \), respectively (red open arrows). These accelerations must be balanced with the Coriolis force (blue open arrows) acting on anomalous ageostrophic motions \( u'_a \) (blue solid arrows) that are westward and eastward around the cyclonic and anticyclonic centers, respectively. In the upper troposphere where \( U_g > c \), the overall structure of the wave train thus yields \( |u'_a \psi'| > 0 \), which corresponds to eastward energy flux or downstream development of disturbances. It is readily observed from the above explanation that this downstream development becomes more effective for the disturbances with more pronounced meridional elongation, due to the stronger eastward advection of meridional wind momentum.

**APPENDIX B**

**Results for Eddies Defined as Local Departures from Zonal Means**

In this study, subweekly atmospheric fluctuations are analyzed to elucidate the roles of migratory transient disturbances in the BAM variability. By contrast, many of the previous studies on the BAM focused on eddies that are defined as local departures from zonal means (e.g., Thompson and Woodworth 2014; Thompson and Barnes 2014). Those eddies include not only subweekly transient disturbances but also low-frequency quasi-stationary anomalies and stationary eddies. In this appendix, the corresponding results for eddies extracted as departures from zonal means are compared with those presented in section 4. Specifically, an EOF analysis has been applied to zonally averaged anomalies of EKE = \( (u'v' + v'u')/2 \) in place of TKE, where asterisks denote the eddy component. In this appendix, the PC1 time series of [EKE] (not [TKE]) is referred to as the BAM index. Other aspects of the analysis (e.g., analysis period, EOF domain) remain the same. As presented by Thompson and Woodworth (2014), the BAM extracted by this method represents the hemispheric-scale pulsing of EKE with a high degree of zonal uniformity.

Figures B1a and B1b show lower-tropospheric poleward eddy heat flux \( -v^*T^* \) and the correlation between \( -v^* \) and \( T^* \) (cor.\([\omega, T^*]\]), respectively, both calculated separately for the positive and negative phases of the BAM. Relative to its negative phase, \( -v^*T^* \) increases over the extratropics in the positive phase of the BAM, consistent with Thompson and Woodworth (2014), while cor.\([\omega, T^*]\) slightly increases only on equatorward side of 45°S. This modulation of cor.\([\omega, T^*]\) is almost the same between \( \omega^* \) and \( T^* \) is not significantly modulated associated with the BAM (Fig. B1d), while \( -v^*T^* \) increases over the extratropics in the positive phase (Fig. B1c).

Figures B1e and B1f show upper-tropospheric poleward eddy momentum flux \( -(u'^*v'^*) \) and the correlation between \( u'^* \) and \( -v'^* \) (cor.\([u'^*, v'^*]\)), respectively, both calculated separately for the positive and negative phases of the BAM. In the positive phase of the BAM, \( -(u'^*v'^*) \) increases over the extratropics, representing the enhancement of eddy momentum transports from the subpolar to the midlatitude PFL. Meanwhile, cor.\([u'^*, v'^*]\) is almost the same between the two phases. In other words, there is virtually no differences in horizontal tilting of eddies, thus making no contribution to the anomalous \( -(u'^*v'^*) \).
Figures B1g and B1h show the corresponding results for the eastward component of the upper-tropospheric extended EP flux \([u^\ast v^\ast - u^\ast u^\ast]\) (or wave-activity flux) and the ratio of the standard deviations of \(u^\ast\) and \(v^\ast\) \(\left[\sigma(u^\ast)/\sigma(u^\ast)\right]\), respectively. In the positive phase of the BAM, a significant increase of \([u^\ast v^\ast - u^\ast u^\ast]\) is detected in the extratropics relative to its negative phase, representing the enhancement of downstream development. Furthermore, \(\left[\sigma(u^\ast)/\sigma(u^\ast)\right]\) increases in midlatitudes, which represents enhanced meridional elongation of eddies that certainly contributes to the enhancement of \([u^\ast v^\ast - u^\ast u^\ast]\).

In summary, the BAM-associated modulations in baroclinic structure (cor.\([-v^\ast, T^\ast]\)) and meridionally elongated structure \(\left[\sigma(u^\ast)/\sigma(u^\ast)\right]\) are hinted for eddies defined as local departures from the zonal means. However, their modulations are less distinct than the corresponding modulations for subweekly transient disturbances shown in section 4. For example, modulations in horizontally tilted structure of eddies (cor.\([u^\ast, -v^\ast]\)) cannot be detected. By focusing on subweekly transient disturbances, the significant contributions of their structural modulations to the hemispheric-scale pulsing of their activity are elucidated as in section 4.

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